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HARNESSING THE SUN

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(Stories About Semiconductors)

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КЛЮЧ К СОЛНЦУ

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HARNESSING THE SUN

LIGHT BECOMES FUEL

Oceans of energy pour to the Earth from the Sun, yet man has had to burrow into the crust of the Earth to get coal and oil to supply energy for industry, light and heat. Ironically, man is tapping solar energy which prehistoric plants absorbed before they turned to coal.

Plants absorb less than one per cent of the solar energy reaching them. Small as this is, only a fraction of it is released from plants which have become coal. Man has had to put up with this wasteful "technology", though he has penetrated the depths of the atom, designed miraculous robots, and has been hurling rocket after rocket into space. The reason is obvious: man has so far been unable to utilise solar radiation without the intermediary vegetable metamorphosis. Still, tapping the Sun's rays and making them work has always been his fondest dream.

Many ancient nations worshipped the Sun. They divined that it was the source of motion and life.

Thy rays embrace all worlds we know
And all thou hast created in them,

sang the Egyptians in their paean to the Sun. Represented as a disc emanating rays, each ending in a hand, the Sun was thought to be a bountiful sovereign showering earthly blessings into the chalices of eager supplicants. The ancients also represented the Sun as a workman, his hands reaching out to the plants to give them light and warmth.

The Sun was anything but a reliable worker. He did what he liked, snatching water from the seas and oceans, raising terrific hurricanes and dissipating his gifts over the Earth. All of man's attempts to curb the Sun's rays came to nothing. The rays scattered far and wide slipped through his fingers. Where was he to find a storehouse to collect the Sun's rays as cunningly as plants did?

There was no choice other than making the fullest use of "conserved sunrays", as K. Timiryazev called the vegetable world. Primitive man learned to nurse a flame and later to make fire. In other words, he learned how to get heat out of the solar radiation which plants had already transformed into chemical energy. Thousands of years were to pass before another step was taken: man built a steam engine, converting heat into mechanical energy. Finally came the age of electricity when mechanical energy was converted into electrical power.

Here we have the whole tortuous process whereby solar radiation travels from the green leaf to the electric bulb, with inevitable losses at each stage.

Various water-heating devices used to be the first solar batteries made by man. Then came mirrors concentrating reflected Sun's rays, and with them the possibility of converting heat into electricity, instead of merely conserving heat in water. The world's first high-capacity solar electric station is near completion in the Ararat Valley, Armenia.

Revolving around a steam boiler installed on a tower, an endless train of mirrors will focus solar radiation on the boiler from dawn to dusk. The rest is the familiar routine: the water turns to steam, the steam turns a turbine and the turbine furnishes the torque for a generator.

Remarkable as this installation is, it omits only one stage—radiation turns into heat without the intermediary link: the conversion into chemical energy. It would be a triumph indeed if one could convert solar radiation directly into electricity!

It is precisely this process which occurs in semiconductor photocells.

Many things cannot be understood overnight. We can read sometimes about our parents' surprise at hearing the first radio sets conjuring sound from the air. Still earlier experiments in electricity, the first "horseless carriages" and the first aeroplanes, each created a sensation.

It is harder to surprise anyone nowadays when the progress of science is so breath-taking and rockets rove through outer space. Still, the operation of a photocell does seem a miracle.

Imagine an electric fan going full blast in a room. Its flex extends to a disc or rectangle made of small dark-bluish mosaics and placed on the window-sill?

Can this possibly he the fan's source of energy?

So it seems, for the fan stops running as soon as you put your hand between the light and the device. Take your hand away and the fan whirls again. The fan's fuel is light which these petal-like plates (a fraction of a millimetre thick) convert into electricity.

These plates, made of silicon, transform 10 or even 15 per cent of the incident solar energy into electricity. In other words, the efficiency factor in this case is 10 to 15 per cent. Several mosaics make up a solar battery, a new generator of electricity.

Solar power plants need no complicated machinery, nor do they require any costly chemical raw materials such as

coal or oil. Surprisingly enough, they are many times as efficient as any other electrical generators.

Man has at last found a means of obtaining energy directly from the Sun. Pressed into man's service is not the mere dribblet of solar energy stored by plants, but the "King of Nature" himself.

IN SPACE FLIGHT

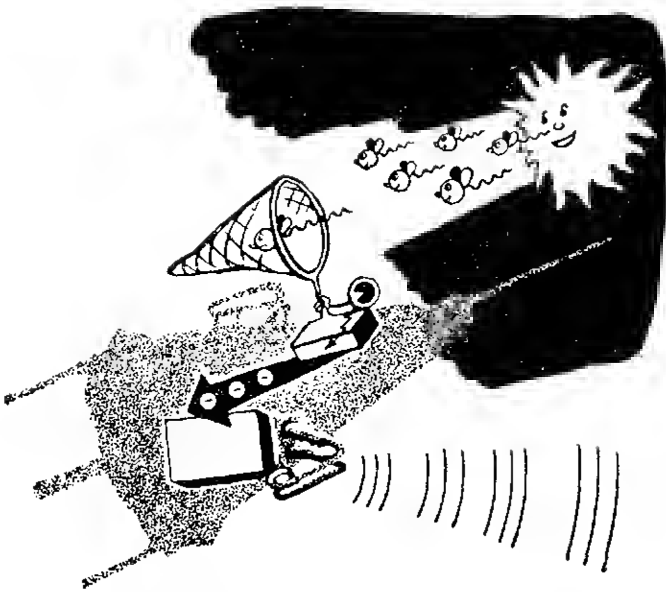
The first solar batteries in our country appeared in the Festival, Kristal and Solnechny miniature radio sets. After this test, Soviet photocells went into outer space in Sputnik-3.

The satellite's battery had nine sections, four bigger ones on the sides, one at the rear and four smaller ones in front. No matter which way Sputnik-3 turned, one of its sections was sure to catch a certain amount of light and thus generate electricity for the radio equipment telemetering data to Earth. Solar radiation made possible these radio messages from outer space.

The satellite could not be in the Sun *all* the time, of course, and the chemical batteries took over whenever it was in the shade. Still, the bulk of the work was done by the photocells. They operated faultlessly and powered the sputnik for 18 months. Chemical batteries alone could not have coped with the job and they did not in fact last as long as the satellite did.

Frequent references have been made to the importance of semiconductor photocells as durable sources of power, indispensable for space rockets and satellites.

Three Soviet sputniks were followed by the Sun-orbiting Mechta rocket, Lunik-2 which took the Soviet pennant to the Moon, and Lunik-3 with its automatic interplanetary station. Later another interplanetary station was launched —this time towards Venus. Finally man shed the shackles of the Earth's gravitation: Yuri Gagarin, Herman Titov, Andrian Nikolayev and Pavel Popovich surprised the world

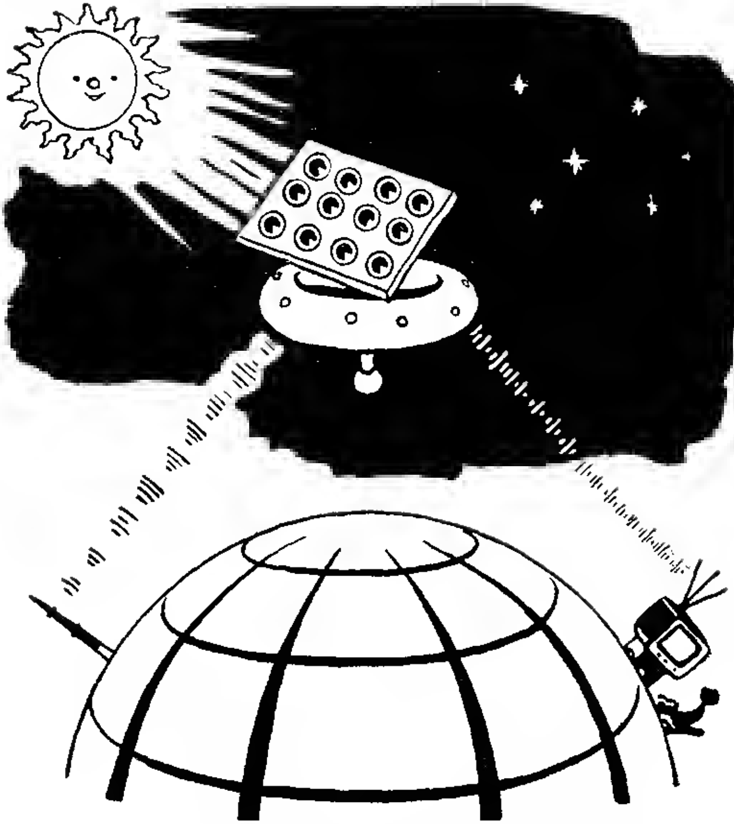


Radio stations all over the world tuned in for the signals of the Soviet automatic interplanetary station and Sputnik-3. These signals were actually the Sun's rays converted by photocells into electricity and by transmitters into radio waves

with their unprecedented flights—these peaceful victories for the Soviet Union.

It was solar radiation that provided the primary source of energy for their radio equipment.

The automatic stations had chemical batteries in addition to photocells. However, in the rockets and satellites of the future (at least in those designed for long flights) solar batteries will most likely be the only sources of power, and batteries charged by them will take over in the shade. Round-the-world television, so often discussed nowadays, will probably be equipped with similar sources of power.



A solar battery will power a TV-relay satellite for a worldwide TV hook-up

Nor will spaceships of the future be able to do without semiconductor solar installations. The latter will also be used to power the contemplated observatory on the Moon.

Faultless operation of the batteries installed on board Sputnik-3 gives us every reason to believe that these batteries have a great future before them in space research. Sputnik-3 carried two experimental batteries (besides the

nine sections already mentioned) for special space tests. We know now that meteoric particles scarcely, if at all, damage the surface of the photocells. Nor do cosmic rays seem to interfere with their work to any noticeable extent, while the temperature of the batteries does not rise above 30° C, since they switch on and off in turn as the satellite revolves. Solar radiation outside the atmosphere is at least half as intense as at the hottest spot on Earth on a clear day. It was feared that the batteries would overheat because of this. But silicon photocells have proved to be rather insensitive to heat (within certain limits, of course). Their efficiency drops by half at 100° C, but returns to normal when cooled.

But silicon is not the only material suitable for solar batteries. Better substances have been obtained. What has been achieved may therefore be regarded as the first page in the solar battery's service record.

Nor is outer space the only field of promise for photocells.

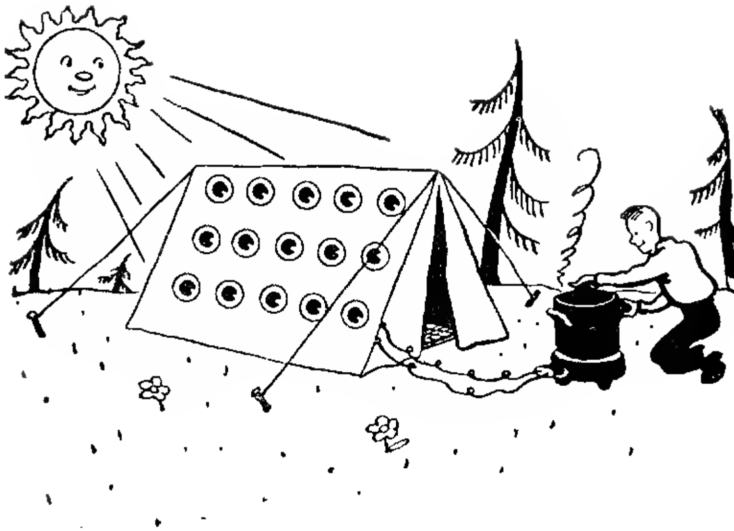
POWER-GENERATING ROOF

Flashes split the darkness over the river as the lightbuoy sends out its signals at regular intervals.

No watchman bothers to visit the lightbuoy to switch it on in the evening or off in the morning. Nor is there any need to change any batteries, it's a sun-powered lightbuoy. A wafer-shaped solar battery beneath the powerful lamp can, within a day, charge the batteries to keep the lamp and intermittent switchgear working for seven nights. Thus even the longest spells of bad weather, incessant rains and mists will not put the lightbuoy out of operation. Photocells switch the device on at dusk and off at daybreak.

* * *

A group of tourists are camping out. They have spread a tarpaulin studded with badge-like photocells. Combined



A "solar carpet", a tent studded with photocells, can cook better than a camp fire or alcohol burner

with an electric range, this "solar carpet" is the best camp kitchen.

Or there is an improved device of the same kind, consisting of a rigid plate with photocells on a metal support. If pivoted, the plate can be kept perpendicular to the sunrays.

Solar lightbuoys, solar carpets and pivoting plates are no longer science fiction, they already exist. In a few years, moreover, solar batteries will power automatic locks and pumps of irrigation networks. An installation similar to a pivoting plate, but larger and with a capacity of several kilowatts, will turn any desert spot into a flowering oasis. Solar energy will draw up underground water to quench parched field and orchards. It will run farm motors, and provide lighting for homes. The rotating, massive plate of the installation will always face the Sun.

A small photocell will do wonders on the roof of a house in sun-steeped areas. These power-generating roofs will be useful even where electricity from conventional sources is available, since the power they generate is cheaper.

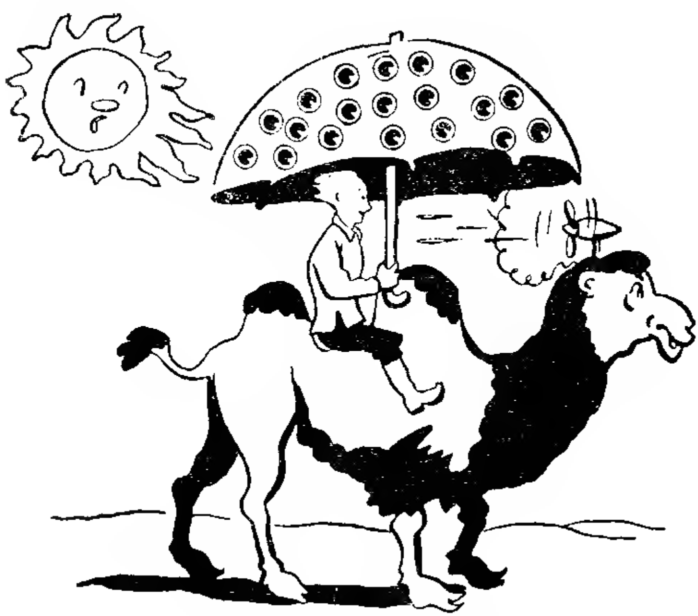
The word *heliofication* will probably come to be just as common as *electrification* is today.

ON THE THRESHOLD OF THE SOLAR AGE

In the long run, man will design large industrial photoelectric power stations, not just solar batteries.

One square metre of a normally sunny area, covered with silicon photocells will produce 100 watts. One square kilometre will generate 100,000 kw.

Soviet Academician A. I. Berg has calculated that a photoelectric power station drawing solar energy from one-



Nothing like a cool puff of air

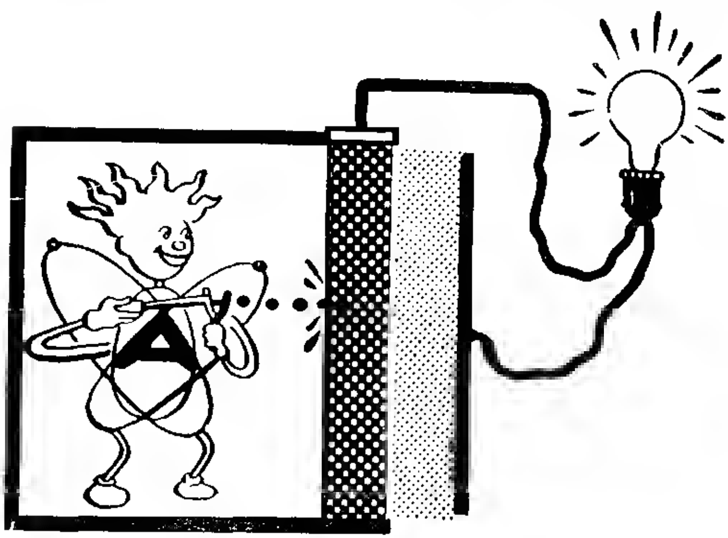
sixth of the surface of the Kuibyshev Sea would have the capacity of the Lenin Hydropower Station on the Volga, the world's second largest.

A calculation even more striking was made by the late F. Joliot-Curie in a report to Soviet scientists some years ago.

"If we could use 10 per cent of the solar radiation over an area the size of Egypt, with the aid of the necessary equipment, the energy obtained would equal the energy now generated in all countries put together."

This means that if we use equipment with the efficiency already attained to cover a fraction of the Sahara, man's need for electric power will be satisfied.

Efficiency, too, is bound to increase with time. Semiconductors now convert only 10 to 14 per cent of the incident solar radiation, the rest being dissipated by reflection off the silicon plates or consumed in the heating of them. The



The atomic battery, a silicon photocell coated with radioactive strontium, is too weak and short-lived to be of much use today. But more advanced types will perhaps come in time

reflection loss is likely to be reduced by using a special coating. It is also possible that a material that will convert less energy into heat can be selected. It is believed that the efficiency of silicon photocells can be nearly doubled. The theoretical limit, using only visible light, is as high as 22 per cent.

Ultraviolet and infrared rays also carry solar energy and could be converted into electricity, thus substantially increasing photocell efficiency.

Here is one possible scheme suggested by physicists: suppose we have a three-layer battery in which each layer absorbs only a part of solar radiation, and passes the rest. Let us assume that the upper layer absorbs only ultraviolet rays, the middle one visible rays, and the lower one infrared rays. The theoretical efficiency of this battery should come up to 40 per cent.

But even that is not the limit, scientists tell us. We can choose a photocell material which would have a single layer absorbing rays of all three kinds. Then the theoretical efficiency should be 65 per cent.

Obviously, both schemes will have to be checked in practice. Nevertheless, the prospects are quite encouraging.

We can already foresee the advent of a solar age which will draw upon the inexhaustible sources of solar radiation for all the energy mankind needs.

But why should we wait? Perhaps we can build photoelectric stations now?

The snag is the cost of the silicon batteries. One of the most common chemical elements, silicon, is suitable for photoelectronics and radio engineering only in a highly purified state, and this is what impedes the development of solar power today.

Fortunately, photocell silicon need not be as pure as silicon for radio engineering. And since radio designers are quite sure that a highly purified silicon will soon be cheaper, designers of solar batteries have also reasons to hope.

When a plate of copper is laid on another of bismuth and connected to a galvanometer, its needle deflects slightly. This was first shown in a series of experiments in 1821 by Seebeck, a Berlin physicist. A century had to pass, however, before the results of these experiments came to light again.

The physical concepts of that day differed a great deal from those prevailing now. Weight was regarded as the only unquestionable property of tangible matter. Physical phenomena involving other forces were interpreted in terms of invisible and imponderable substances. That was how the concepts of electric and magnetic fluids originated.

Shortly before, in 1820, the Danish physicist Oersted discovered that a magnetic needle deflected near a live wire. That meant magnetic phenomena were caused by electricity and physics had to renounce one of its imponderables.

Seebeck, however, was among the doubters. To check his premise, he took two plates of different metals (Volta had shown that the pair must generate contact electricity) and connected them to a multiplicator, as the first galvanometers were called. The needle deflected whenever he pressed the ends of the wires to the plates. So Oersted was right after all. But real physicist that he was, Seebeck was not to be persuaded so easily. Once, in Jena, he had embraced a new theory much too readily and he had learned his lesson. His close friend, the great poet and naturalist Goethe, had been evolving his own theory of colours, according to which there are only two *pure* colours, white and black. When mixed they produce all other colours as they were but different shades of chiaroscuro.

At first Seebeck had shared Goethe's view as the Newtonian doctrine seemed to him much too artificial. How

could it be that any white beam, however, slender, consisted of seven streams of light particles corresponding to the seven colours of the rainbow! But when the wave properties of light were discovered, colour combination was no longer a mystery, and Goethe's followers promptly abandoned his theory.

This time Seebeck decided to be more cautious and check his experiment carefully before drawing conclusions. The first suspicion that crossed his mind was that the moisture of his hand had something to do with the effect. When he pressed the contacts again, he put a wet strip of paper between them and his fingers. There was no effect. When he used glass or metal instead of paper, the pointer deflected, though not so promptly.

Seebeck saw the light: the warmth of his hand was at the bottom of it all! The different temperature potentials between the wires and the plates, on the one hand, and between the plates themselves, on the other, were responsible for the magnetic phenomena.

Then the scientist modified his experiment. He bent the plates, soldered the ends together, put a magnetic needle between them and heated one of the soldered junctions over an alcohol burner. This time it worked! The needle came to life and returned to its original position as soon as the burner was taken away.

Many physicists opined that the deflection showed that there was current in Seebeck's circuit, and that *proved* Oersted's experiment rather than refuted it.

But Seebeck would not give in.

In one respect he continued to be a follower of Goethe: he conceded nothing to his opponents. Just as Goethe had vehemently accused Newton of "cunning and deception", Seebeck declared that all conscientious scientists must share his view. The Oersted's discovery was nothing but a fickle vogue, in his opinion. The Berlin non-conformist insisted that magnetism and electricity were not related.

Seebeck called his effect thermomagnetism, and asserted that heating magnetised metals. He tried to account for the Earth's magnetic field hy ascribing it to the difference of temperatures at the poles and the equator, which he claimed was in direct proximity of a volcano-heated belt of metals and ores.

That was a delusion, of course. What Seebeck had done was to convert heat into electricity for the first time, though he himself was the last man to suspect it. The phenomenon he discovered soon came to be called thermoelectricity and not thermomagnetism.

AVENUE AND ALLEY

Seebeck's controversy with his contemporaries was short-lived; his discovery made no stir and his experiments were soon forgotten.

Oersted's experiments were followed by the research of Ampere, that "Newton of electricity", as Maxwell called him, and by the studies of many other scientists. Faraday, for instance, discovered electromagnetic induction hasic to the operation of nearly all electrical machines: motors, generators and transformers.

These great discoveries paved the way for the rapidly developing theory of electricity, while Seeheck's effect still remained a blind alley.

Apart from the hismuth-copper pair, Seebeck had studied a host of materials, including those now known as semiconductors. In his day, however, no one could see their value: they were regarded either as faulty conductors or poor insulators. Metals, on the other hand, yielded negligible effects in Seebeck's experiments. A soldered pair of metal wires, known as thermoelement, yielded several thousandths of a volt at the highest temperatures it could stand short of melting.

Many attempts were made to use thermoelements as sources of energy. Inventors groped for the most suitable

pair of metals. Platinum-bismuth pairs were found to be better than aluminium-copper pairs for the same difference of temperature. Special alloys were produced, and their combinations gave still better results. But the best alloys and best design of the system never brought efficiency as high as 1 per cent, usually it was as low as 0.5 per cent.

To obtain voltages suitable for practical purposes, thousands of elements would have to be connected in series; and that would make the generator so cumbersome that its inner resistance would consume all the energy generated. No wonder many noted scientists believed that thermoelectricity was suitable only for measuring temperatures, and that its chances as a commercial source of power were nil.

However, Academician Yoffe, an outstanding Soviet physicist, viewed the matter in a different light.

Let us recall the period. "Sound photography" and an aeroplane-ground communication were feats of engineering. Trams were the chief urban transport and the cinema was styled "moving pictures". Any attempt to work semiconductor miracles was bound to appear fantastic in those days.

Nevertheless, the scientist insisted in articles and lectures that a great future awaited semiconductors. He became the most fervent populariser and indeed the most persistent investigator and sponsor of research in this field. As a scientist he was especially attracted to thermoelectricity. In 1929 and 1930 he declared in the press that this field of research would be of great value in the generation of electricity. A thermoelectric generator, he held, should be built not of metals, but of semiconductors, for that would raise its efficiency to 4 per cent, or even more, making it suitable for the commercial generation of electricity.

Aided by his enthusiastic team, Yoffe kept trying out different materials. To begin with, they had to yield the greatest thermal emf possible, as the maximum voltage

across the soldered plates is called. For this reason the voltage across the cold ends of a thermoelement, or thermel would repeatedly be measured while the junction was being heated. Two other important requirements were: high electric conductivity (the plates should not be heated too much by the current, or most of the electric energy generated by a thermel would be wasted) and low thermal conductivity (as little heat as possible should flow across the plates).

Besides, the thermel had to resist overheating: it should neither oxidise, nor crack, let alone melt at low temperatures, for the higher the permissible temperature, the greater the difference of temperatures between the hot and cold ends, and the more efficient the generator as a whole.

Was it easy to meet such a set of requirements?

"It is difficult, but by no means impossible!" was the scientists' verdict. They tested many different combinations until they settled on tellurium compounds. In 1940, less than a decade after Yoffe's start in thermoelectricity, the efficiency of semiconductor thermopiles was raised under his guidance to more than 3 per cent. Now it is 8 and even 9 per cent.

In other words, thermopiles can vie with small steam-engines in efficiency. At the same time they are much simpler, have no moving parts, and, last but not least, transform heat directly into electricity, by-passing the mechanical-energy stage.

Curiously enough, Seebeck's semiconductors could have heen used to make a thermel with a 3 per cent efficiency, the same as of the best steam-engines of his time. Nowadays, thermopile is again rivalling steam-engines, and it is very unlikely to be again consigned to the backyards.

Who would now dare to say that thermoelectricity was a blind alley, scientifically and technologically? On the contrary, it has broadened into a large avenue and promises to become a new industry.

Though it is not long since the Institute of Semiconductors of the U.S.S.R. Academy of Sciences launched its thermoelectricity research, an enormous number of combinations has already been tested, and many of the apparatus designed stock a hig and unique museum.

Our institute guide was Anatoli Voronin. We were shown a "samovar", as one of the first thermogenerators was nicknamed because it looked like one. The water in it cooled the ends of the thermels until the "samovar" was set boiling. The thermels, rows of round or square columns held together in pairs by metal plates, were thrust into the heart of the "samovar" through its "chimney" to where the furnace of a real samovar would be. The outer surface of the apparatus had a pair of terminals, just as any source of current should.

We also saw a generator which looked like a honeycombed "Chinese fan". Instead of tanks, it had metal, air-cooled fins. This system proved to be simpler and survived in all subsequent apparatus. Like the "samovar", the "fan" had a coal furnace and was later rejected for that reason.

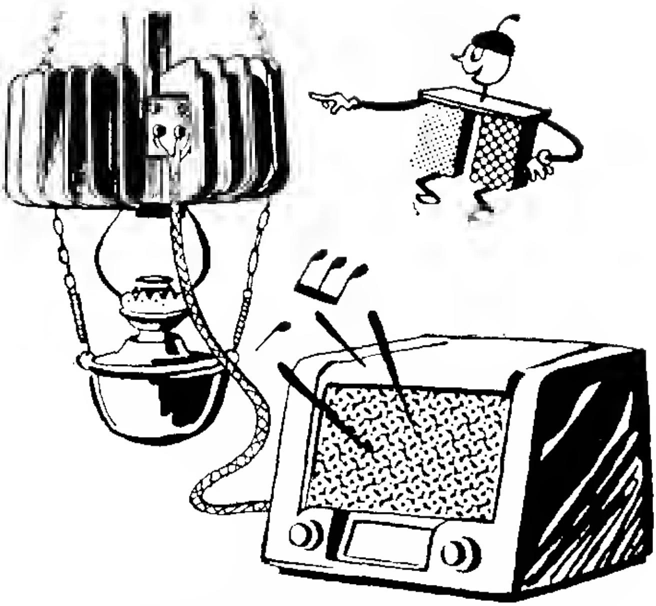
We were shown the famous Molnia oil-lamp three-watt thermopile, or the TГK-3 for short.

An ordinary oil lamp, it can power a radio set after a special finned jacket has been slipped over the neck of the glass chimney. No additional oil is needed.

The temperature of the internal hot ends of the thermel is 380° C, and of the cold ends, from 60° C to 80° C. With a difference of temperatures of about 300° C, the device generates enough energy to power d. c. radio sets.

The lamp reservoir bolds about $1\frac{1}{4}$ pints of oil, lasting 8 hours. The life of the generator is 4,000 hours. Which means that it will last at least five years, if used for two or three hours a day.

Thousands of these "oil-lamp plants" can now be seen in remote areas of the Soviet Union. They have reached



Kerosene thermogenerator KTГ can be seen in an outlaying village and surveyors' tent. *Top right*: a thermocell

India and Indonesia, the Arab countries and Argentina, Ethiopia and Mexico. They are already in production in the People's Republic of China. The Soviet "sputnik-lamp", as it has been dubbed abroad, is used in 30 countries.

The next items we saw were a 15-watt oil-burner thermopile for powering the Urozhai radio station used for communications between collective farms and a one-kilowatt thermopile used for lighting in combination with a small oven. An even larger thermoelectric generator, to be heated by natural gas, has been built in Moscow to supply electricity to gas pipe systems.

Extremely simple and cheap, this equipment will no doubt play an important part in the development of the auxiliary power industry, and perhaps in the development of the large-scale power industry as well. We say

"perhaps" because the conventional thermel now has a younger but much stronger competitor, the plasmic thermel. The theory of the latter was one of Academician Yoffe's last efforts in research.

The plasmic thermel is a gaseous mixture of ions and electrons placed in a vacuum between two adjacent electrodes. Plasma has a low heat conductivity and this is why the system uses heat more effectively than the conventional thermel.

The most exciting thing probably is that plasmic and hard thermels make excellent pairs. The former work better at high temperatures and the latter at lower temperatures, as we saw above. In combination they complement one another: the plasmic element converts part of the heat, and the rest is mopped up at lower temperatures by its hard partner. This two-stage thermogenerator will transform perhaps half of the entire thermoenergy supplied.

Anatoli Voronin described the merits and drawbacks of the different generators, and we could almost trace the advances made in this new field of engineering. The combination of the antiquated oil lamp and the newly discovered semiconductor symbolise the seven-league strides of technology today. It also calls for a new kind of mentality: what might have appeared hardly more than a fantasy yesterday, should now be dealt with in all earnest and interpreted in realistic technological terms.

It occurred to us that the Institute of Semiconductors ought to set up another museum. Its staff should not be afraid of dreaming: they should exhibit the models and graphs of the thermoelectric generators of the future, both imminent and remote. Perhaps something like this....

* * *

Imagine a long, low chamber lined with thermels (two-stage thermels, of course, consisting of plasmic and hard cells) as it might with tiny tiles. Starting right from the

chamber are transmission lines carried by huge pylons. This is what a power station of the future will look like: the chamber is the furnace and the walls are the power generators. There is nothing else: neither steam boilers, nor turbines nor dynamos. A high-capacity power station taking up less room than would a small house!

Or here is a drill hole, its inside also lined with thermels, biting deep into the earth. It is an underground gas producer. The hot gas produced by the coal burning underground gives off its heat to the electricity-generating thermels and then runs on to a chemical works.

Or imagine a ribbed thermopile "slipped over" the crater of a volcano, or still better, sunk into the molten magma beneath the earth's crust. Instead of raging in volcanic eruptions the tamed magma converted into electricity flows through wires.

And, finally, imagine an atomic power station of the future, with nuclear fuel rods encased in tubes of two-stage thermels. Without boilers, turbines, dynamos or any other moving parts, this station, locked and sealed, will run automatically for decades or even centuries—as long as its nuclear fuel lasts.... What a splendid illustration of the peaceful possibilities of nuclear fission.

Later on, when thermonuclear reaction is controlled we shall be able to build semiconductor nuclear power stations, consisting of merely a reactor within a thermopile.

These are encouraging and ambitious projects. But thermopiles face a still greater undertaking, known by the prosaic name of waste-heat utilisation. Only a quarter of the energy from the fuel burnt all over the world is used by man while the rest is dissipated into the atmosphere. Incalculable treasures are tossed away through the smoke-stacks of factories, boiler installations and power stations.

Thermopiles, the descendants of those which are now slipped over oil-lamp chimneys, are sure to appear in smoke-stacks, to convert waste heat into electricity. Or

rather the stacks themselves will be constructed of thermels.

Finally, there will be no chimneys at all: man will no longer burn precious chemicals, coal and oil. Solar radiation will produce electricity directly, and thermels will play a full part in the process. In this field they will probably prove more successful than in any other.

DREAMS REALISED

A few years ago we asked Academician Yoffe which would make a better trap for solar radiation: photocells or thermels?

"I think thermels carry the day", he replied. "They can be heated to very high temperatures by concentrating solar radiation with mirrors, and a high-capacity power station can be built over a small area. One cannot concentrate such energy in the case of photocells since they cannot stand high temperatures."

We visited the Power Institute of the U.S.S.R. Academy of Sciences where solar thermoelectricity studies are in progress and met Alexander Okhotin who is participating in this work.

Our talks threw into relief the principal weak point of thermopiles, and, we must confess, made us doubt whether Academician Yoffe had been right. Judge for yourself.

A thermopile is installed at the focus of a vast concave reflector made up of small flat mirrors, concentrating the sunrays on the hot ends of the thermels, the cold ends being pressed to water-cooled copper pipes. Why do they use water and not air for cooling? Because the pile should be as small as possible and have no ribs which would shut out some of the solar radiation. The water tubing also provides the framework to which the thermels are glued with special heat-resistant and heat-conducting varnish.

Sunrays heat the hot junctions up to 450° C or even 500° C while the temperature of the cold junctions does

not rise above 40° C to 50° C. Thus the temperature ranges between 400° C and 450° C, which ensures a thermel efficiency of about nine per cent. True enough, in the pile there are inevitable losses (for the heating of numerous contacts and wires, for example) and the efficiency of the whole installation is naturally lower. For all that it is more efficient than all sorts of water heaters used in tropical countries.

Yet this pile is a far cry from what a generator could be. We have said that the pile is installed at the focus of a concave mirror. This is not accurate. The temperature at the focus can rise to 3,000° C or even higher. The heat barrier of thermels is much lower and they are deliberately moved away from the focus, into a zone with less intense heating.

The junctions of this pile, as you have no doubt noticed, can resist higher temperatures than those of its predecessors. This is of course a great advance. If this temperature could be brought up to 700° C, with the temperature of the cold junctions remaining at about 40° C, the efficiency would climb to 15 per cent.

"Unfortunately, thermels cannot yet resist intense heat," Okhotin explained.

Meanwhile silicon photocells had been gaining ground and for some time it seemed that thermels stood no chance in competition with them. Recently at the Institute of Metal Ceramics and Special Alloys of the Academy of Sciences of the Ukrainian Republic, Kiev, we were shown thermels of silicon and boron carbides which produced a considerable thermal emf at temperatures up to 1,700° C. True, the lower temperature limit of this experimental instrument does not decrease below 400° C, but even the 400° C to 1,700° C interval is unprecedented. Now, the efficiency of the instrument depends, as we know, on the temperature interval.

Then we realised that, speaking about prospects for thermoelectric generators, Abram Yoffe had had in mind

new materials yet to be discovered. Now they *have* been discovered and their application to the direct utilisation of solar energy is in the offing. Even at that time A. F. Yoffe had evidently good reasons to regard both hard and plasmic cells as thermels. The latter, as we said, far exceed the conventional type and no doubt they will come into their own in solar power installations. This is when thermoelectric generators will prove their worth.

Nor should we neglect another major advantage of thermels over photocells: cheapness.

"Simple calculations will show that solar thermels could generate electricity more cheaply than hydraulic power stations," Academician Yoffe wrote.

The scientist pointed out that thermal, hydro- and atomic power stations should be aided, apart from a small-scale semiconductor power generating industry, by pilot solar power stations.

So we should add a new exhibit to our imaginary museum. . . .

* * *

From a balcony running around a tall pylon we can see a boundless field studded with extraordinary giant flowers. Each flower is a concave mirror polished to a dazzle, with thermopiles instead of the stamens and pistils. The huge sunflower-like mirror-heads slowly turn on their mechanical stalks.

The field is divided into equal strips by barriers which look very much like encased irrigation canals, running away to the horizon. There is one essential difference though: in the usual field the life-giving moisture runs through a canal to the plants, while here solar energy flows into the "plants", then into the encased collectors, and finally through wires to lamps and motors, bringing light, warmth and life.

The capacity of a solar power station of this type can run into scores and hundreds of millions of kilowatts.

Several such stations in a hot climate would be contributor No. 1 to the country's integrated power grid.

Apart from solar energy convertors, all other installations of the future we have spoken about will be built with multi-stage batteries which will have not just two, but three stages: plasmic cells plus the conventional high-temperature and low-temperature thermels which will mop up the heat left over.

New advances open up new prospects, and so new plans are drawn up.

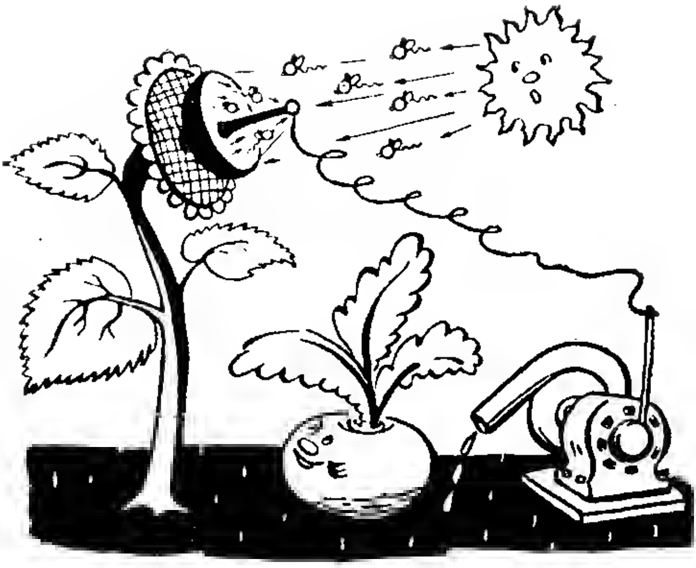
"Our dream leads us on," Academician Yoffe said. "We are now planning to double the efficiency of thermels and if we do they will be able to vie with smaller heat power stations, and later with the best power stations whose efficiency factor hardly ever comes up to 30 per cent."

Now we know that plasmic thermels (obviously in combination with hard high-temperature and low-temperature cells) make this estimate not only realistic but perhaps even too conservative. In short, the prediction has proved correct, and when it is realised, it will be not just a major discovery, but a genuine revolution in science.

Thermels and photocells will serve man well. The semiconductor is a key to the Sun, one of the greatest treasure-houses of energy in nature.

There is yet another treasure-house, however: the atomic nucleus. Once the fission of heavy nuclei is harnessed, science will tackle a still more difficult problem: controlled synthesis of light nuclei. When thermonuclear power stations will have been built, mankind will have an inexhaustible supply of energy. Semiconductor devices converting radiation into electricity will serve well in this field also.

In this connection it is worthwhile to recall that the Sun itself is a giant thermonuclear reactor and its light and heat are thermonuclear products. Thus helio engineering is, in a sense, part of the thermonuclear engineering to come.



A thermopile at the focus of a concave mirror will eventually become a fine solar radiation converter

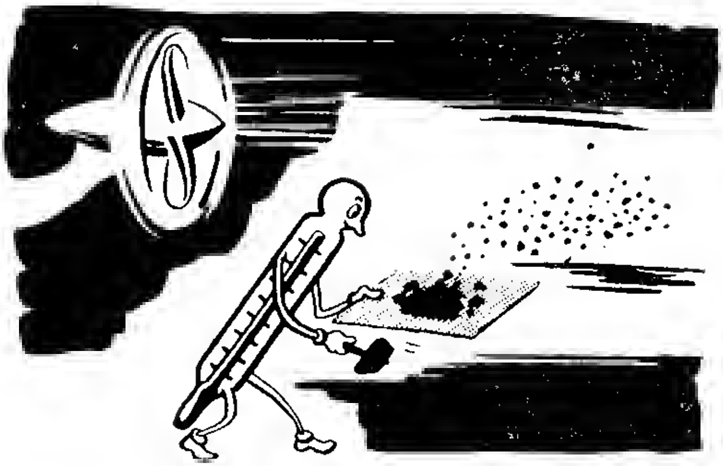
The Programme of the Communist Party of the Soviet Union sets Soviet scientists the task of discovering new sources of power and methods of direct transformation of thermal, nuclear, solar and chemical energy into electricity. The investigation of semiconductors is expected to make a valuable contribution to the solution of this problem. There is no doubt that scientists will rise to the occasion. Suffice it to recall the breath-taking advance of this young field and the progress already made in the study and application of semiconductors as transformers of heat, light and nuclear energy into electricity.

* * *

Now, how do photocells and thermels work? Why do some of them convert light and others convert heat into electric-

ity? We have said that solar batteries are made of silicon and thermopiles of tellurium compounds. But how do these materials differ from metals and insulators? What is a semiconductor?

To answer these questions we shall have to set aside engineering for a while and turn to physics.



SOMETHING NO ONE HAS SEEN

FRIENDLY ENEMIES

There are two friendly enemies in engineering. Neither can do without the other, each helps and guards the other. You all know them very well, but often do not notice them any more than other things around us.

Without them no lamp burns, no trolley-bus runs, no factory works, no radio set sounds. Electricity is impossible without them.

The two are the conductor and the insulator.

Trolley-bus wires are held by insulators. High-tension lines are suspended from link insulators and so on. This is how the two help each other.

The conductor is a canal for a flow of current while the insulator is the emhankment preventing the electricity from leaking. The insulator makes sure that the conductor does not touch a metal pylon, the frame of a machine or

the body of a desk lamp. But while the two guard each other, they are strikingly different. Take an insulator of paraffin, one square centimetre by one millimetre thick, and a copper conductor. Soviet physicist E. I. Adirovich has calculated that a copper wire of the same cross-section (square centimetre) will possess the specific resistance of a paraffin plate if the wire is 1,000,000,000,000,000,000 kilometres long. This is 100 million times the diameter of the solar system or is equal the distance hetween the Earth and the most remote stars of the galaxy. Obviously, there is not enough copper on Earth to make such a wire.

How many times is the resistance of paraffin greater than that of copper? The figure is terrifying: unity and 24 zeros.

Such are the poles of electrical engineering, and everything lying in between was, until recently, regarded as something next to worthless. True, we have taken the extremes: there are metals whose resistance is hundreds of times as large as that of copper and insulators whose resistance is smaller by a factor of several thousand than that of paraffin. Yet even between the worst conductor and the worst insulator there is a gap: unity and a good dozen zeros.

This gap contains a host of materials which are useful neither as conductors nor as insulators. They are called semiconductors, though they might well he called semiinsulators as well.

"WHIMS" OF SEMICONDUCTORS

Semiconductors are not remarkable just because they fill the gap between metals and insulators. Other features have made them more famous.

Changeability is the main feature. The same semiconductor may behave now like an honest-to-goodness conductor, now like a typical insulator, and at other times it may

reveal its own characteristic properties. Its behaviour depends on a variety of reasons, many of which are not easy to detect, so its "whims" seem inexplicable at first glance.

A change in environment may scarcely be perceptible—the mercury rises several degrees, there is a little more light, or the surrounding air becomes somewhat more humid, but the semiconductor behaves quite differently: its electric resistance changes.

This can be shown by a simple circuit made of a semiconductor, a battery and a measuring device. The needle of the instrument will deflect sharply, indicating the sensitivity of the semiconductor to outer changes.

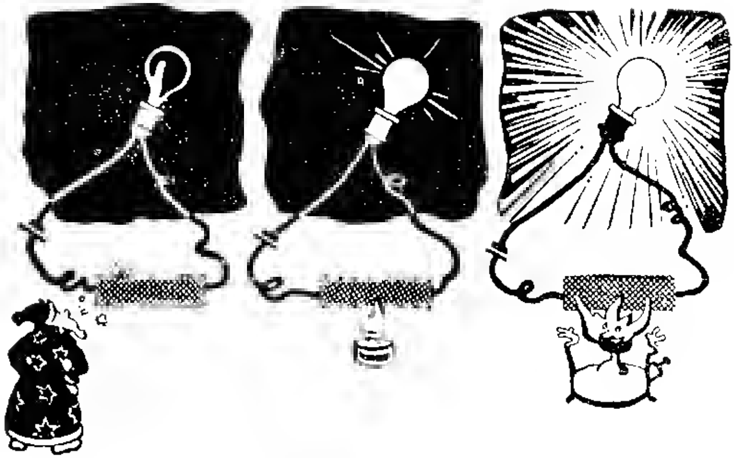
This does not mean that all semiconductors react to such changes in the same way. On the contrary, some of them more readily react to light, others to temperature; some are highly sensitive, others less so. Nor does the sensitivity manifest itself always in the same manner: it depends on the spectral composition of light and on the temperature range.

Many of these peculiarities were unknown a short time ago: they could not be detected without modern analysis techniques. No practical application of semiconductors was possible until these peculiarities had been studied, their potential applications analysed and their properties controlled.

FIRST TENTATIVE ANSWER

Why are these wonderful materials so sensitive to external changes? In what respect do they differ from metals and insulators?

An electric current in metals is a flow of electrons. Within a metal wire there are always many free electrons moving about at random much like specks of dust in a sunbeam. When a potential is applied, that is, a battery is connected across the ends of the wire, the electrons tend to drift in one direction, making a flow of electric current.



Conduction in a semiconductor (or call it a semiinsulator) depends on the temperature: cooling makes it more like an insulator and heating more like a conductor

The application of a potential can be compared to switching on a fan which starts to suck dust through a window. Let us assume, however, that the speed of the random movements of specks of dust is much larger than that imparted to them by the fan. Then our model will be much closer to the actual process.

An insulator is something entirely different. It has no free electrons in it since all of them are bound in the atoms of the substance. This is why no current flows in it. To sustain our metaphor, imagine a plate of burnt clay placed at the window: the fan will not be able to tear off any particles of clay.

Now imagine a sheet of iron with a layer of fine dust spread over it. Suppose you tap on the bottom of the sheet, raising little eddies of dust. If you switch on the fan somewhere near the sheet the specks will be sucked towards it. The stronger you tap on the sheet, the more dust will drift towards the fan in the window.

This simple experiment helps us to understand the processes at work in a semiconductor. The electrons in a semiconductor are bound in the atoms, but not so firmly as in an insulator. In any substance atoms are in constant thermal agitation. The higher the temperature, the more rapid their motion, and the more atoms collide. These collisions cannot knock an electron out of an insulator atom: it is bound too firmly. But in a semiconductor this happens from time to time, and some electrons become loose (this corresponds to the tapping on the sheet).

It is these released electrons which produce a flow of current in a semiconductor.

At low temperatures the atoms move slowly, few electrons are released, and no current flows. At absolute zero, —273° C (which cannot be attained in practice) the thermal motion of particles ceases entirely and the semiconductor becomes an insulator.

At higher temperatures the atoms move more rapidly, their collisions tear away electrons more frequently (just like stronger tapping will raise more specks of dust in the air) and a flow of current in the semiconductor increases.

"ETIQUETTE" AMONG ELECTRONS

This explanation gives only a very rough idea of what really happens. For a more specific description, we have first to get an insight into a crystalline solid or even into its atom and to try to visualise what no one has actually seen but what has been established indirectly with careful experiments and complex calculations. The fact is that this microcosm is strikingly different from the microcosm familiar to us.

A coin is a smooth, solid object. Put it on a table and it will lie at rest: at least this is how it is perceived by our senses. Actually, the coin is a multitude of minute particles accounting for a mere fraction of its volume. These particles are in constant motion: some oscillate

around certain mean positions, while others rush about, colliding with each other and racing on, forward, backward, right, left, up and down.

Each atom is a universe in itself and there are hundred millions of them—more than people on Earth—in one tiny invisible bacterium.

A few decades ago an atom was conceived of as something like a solar system: a round, solid nucleus with ball-shaped electrons orbiting it. This is how the atom was drawn schematically, and rough as this model is, it is still used.

The advance of nuclear physics has revealed that the atom has an extremely complex structure.

To begin with, it has become clear that the particles of the atomic microcosm cannot be compared either to balls or to specks. The wave nature of matter, imperceptible in large objects, becomes evident in these tiny particles. A stream of electrons inside a substance does not behave like a volley of shot but can, for example, get around obstacles, much like water does.

Besides, each electron in an atom is not a point, but rather a cloud stretching all over the orbit. These electron clouds surround the nucleus in several layers.

In a vacuum a released electron is even more diffuse than in the atom. Yet in some cases it behaves as though concentrated at one point. Such is the double nature of the electron. It is neither a hard piece of matter, as was thought once, nor an aggregate of waves, as was thought later. The electron possesses both the properties of a particle and a wave and the motion of electrons in an atom is far more involved than that of the planets around the Sun.

We can imagine that due to an external force (the attraction of another star passing close to the Sun, for example) one of the planets, presumably the most remote, may change its orbit and recede gradually from the centre of the solar system. Or conversely: should the solar gravitation of a planet increase all of a sudden (we shall not dis-

cuss whether it is possible) this planet will gradually approach the Sun.

Electrons behave quite differently. The orbits in which they move around the nucleus are called energy levels since their spacing in the atom is determined by their energies. The higher the energy of an electron, the weaker its attraction to the nucleus and the farther its orbit from the nucleus. An electron cannot possess an arbitrary amount of energy—it cannot pass from one state to another gradually. In the atom there can be only definite allowed energy levels with forbidden gaps between. If an electron—the "Earth"—receives additional energy it is bound to jump away from the "Sun" and enter the orbit of "Mars", and if it loses energy it jumps into the orbit of "Venus".

The electron cannot gain or lose just any amount of energy, but only definite portions of it known as quanta. Light consists of quanta or photons, the elementary portions of radiation. As the electron absorbs or emits light it passes from one quantum state into another. The same occurs when it receives energy from another source, from atomic thermal agitation, for example, or transfers it to the atom in the form of heat.

Nuclear physics today is based on the theory of elementary particles in motion—known as quantum mechanics. Absorption and emission of energy in definite portions constitute its basic proposition, energy quantisation.

According to another important law of this theory, there can be only one electron in each quantum state. If an electron's energy was the only characteristic of the quantum state, all electrons in the atom would be spaced at different distances from the nucleus, strictly in accordance with their energies. Actually, this is not the case. The quantum state is determined by other quantities, apart from energy. It is not necessary to discuss them, we shall merely note that several electrons can possess the same energy (and consequently be at the same distance from the

atomic nucleus), which does not contradict the principle that there can be only one electron in each quantum state, since the quantum states of these electrons differ not in energy, but in other characteristics.

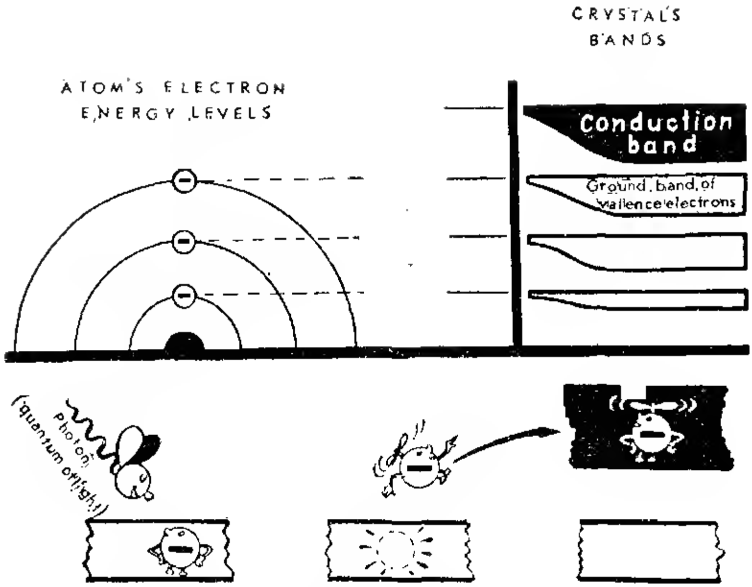
So the electrons are spaced in the atom in groups—in accordance with the Mendeleyev Periodic Law. The group closest to the nucleus consists of only two electrons. In hydrogen, the first element of the periodic system, the shell is not filled up, since only one electron moves around the nucleus. In the second element, helium, the shell is already completed. Then from lithium to neon, electrons begin filling up a second shell until it carries eight electrons. Similarly, a third shell holds a maximum of 18 electrons, the fourth a total of 32 electrons, and so on. The heavier the element the lower its place in the Mendeleyev Table and the more shells in its atom.

All shells correspond to definite energy levels with electrons at each. There can be no electrons, however, in the gaps. Thus, allowed levels and forbidden gaps alternate, which, as we know, is a direct corollary of the principle of energy quantisation.

If we take a crystal instead of an atom we shall see another manifestation of the second principle mentioned above.

In a crystal, likewise, there can be no two electrons in the same quantum state. Such is the strict electron "etiquette": the atoms in a body are not just put together like the parts of a jigsaw puzzle. They interact with each other. As though obeying a code of courtesy, each of them makes room for others. As a result the quantum states of the electrons differ at the same level. The electron energy levels "split" into a series of close, yet distinct levels, making up allowed and forbidden bands.

If we represent these bands graphically, the allowed band of the electrons closest to the nucleus and poorest in energy will be the lowest; somewhat higher we shall have the forbidden band, then the allowed band of the next



Top: electron orbits in an atom (known as electron energy levels) and bands in a crystal. *Bottom*: an electron which has received a photon, an additional energy of a quantum of light, jumping from the ground band to the conduction band

group of electrons, then the forbidden band again, and so on.

Not all these bands are of equal interest to us. The electrons in the complete shells are firmly bound in the nucleus and have no part either in chemical combinations of atoms, or in electric conductivity. Both functions are performed by the electrons of the incomplete outermost shells whose connection with the nucleus is the weakest: they are called valence electrons. The name comes from the Latin word *valentia*—power—and refers to their power of joining and keeping other atoms.

It is the behaviour of valence electrons which accounts for the differences between metals, semiconductors and insulators. The bands which carry valence electrons are

of special interest, therefore, for the study of the electric properties of a solid.

And this leads us to the crux of the matter.

Which valence electron bands are allowed? First of all the highest of the bands we have mentioned: the band which belongs to the outermost shell. On top of it there is another band, known as the excitation band to which an electron leaps after receiving an additional portion of energy due to an atomic collision or the absorption of a quantum of light.

Once in the excitation band electrons begin to move freely in the crystal lattice and the crystal becomes a conductor. That is why the excitation band is also known as the conduction band.

Imagine a two-storey garage, its ground floor representing the valence band, the upper floor the conduction band, and the distance between the floors is the forbidden gap.

Cars on either floor, or both, will complete our rough model of the electric properties of any material.

Suggested by the American scientist Shockley, this illustration has become world famous. But for our purpose, since cars cannot jump from one floor to another, it is not sufficiently illustrative. Therefore we shall add helicopter propellers to the cars and assume that their speed of rotation increases with temperature. Now our cars can both ride and fly.

The speed of rotation should not, however, be directly associated with that of a jump. An electron jumps from one band to another instantly, and it is actually the number of excited electrons that increases with temperature.

THREE MODELS

Model No. 1: In the garage there is no floor between the storeys. Cars can move freely across the ground floor or in mid-air at any height.

This is a model of metal. It has no forbidden gap. Both filled and empty energy levels are continuous and transitions between them unimpeded. Electric conductivity does not involve electron excitation in this case—there is no need to toss electrons into the higher band, since they can drift freely to any part of the body.

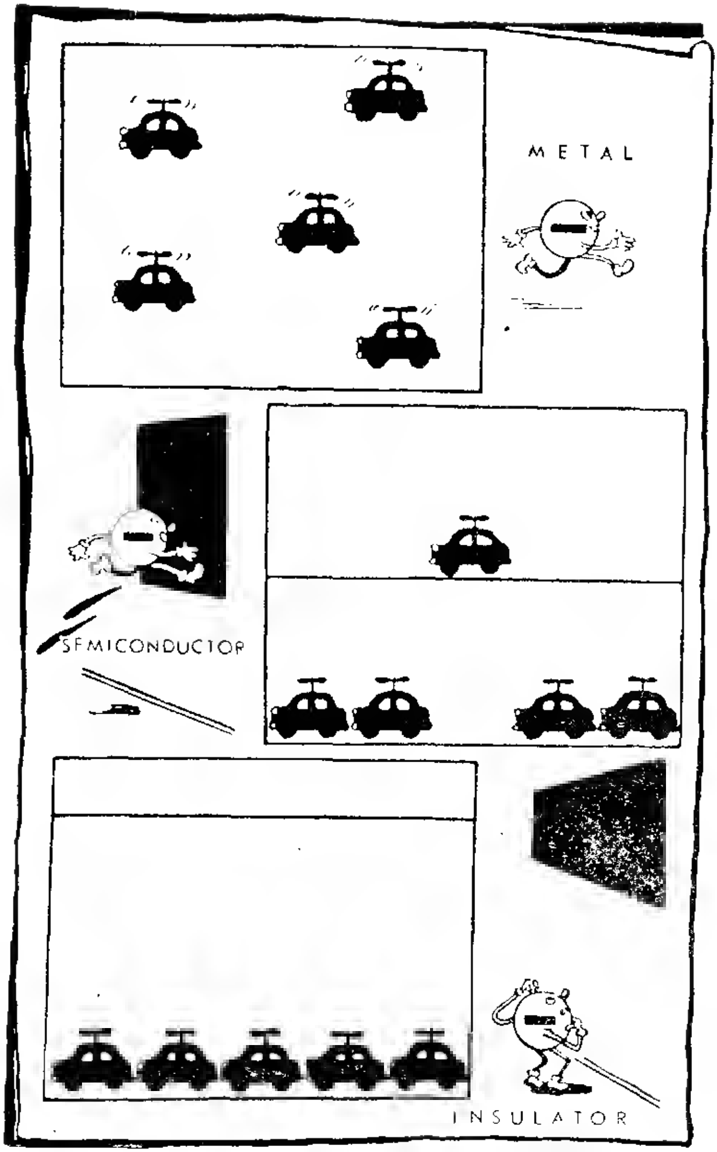
Model No. 2: The ground floor is jammed with cars, but there is not a single car on the second floor. Now, our helicopter cars cannot soar—they have to get to the second floor in one hop. But their propellers are not powerful enough.

This is a model of an insulator. The forbidden gap is very broad and an electron has to receive a large amount of energy to get through. Usually this very seldom occurs only when an atomic collision is very strong. To all intents and purposes we can assume that there are no free electrons in a substance like this and they can appear only when the insulator is punctured by high voltage, which alone can provide the electrons with energy sufficient for the jump.

And here is *Model No. 3*: The garage is a two-storey structure, but the ceiling of the ground floor is not very high. There are close rows of cars on the ground floor, and as well, there are several cars on the second floor.

This is a model of a semiconductor. Its valence band electrons could not get to the second floor if the forbidden gap was as broad as in an insulator. In this case it is much narrower; the ground floor ceiling is much lower. Therefore even at room temperature atomic collisions toss some electrons into the conduction band.

Hence it is clear that according to this band theory the classification of nonmetallic solids into semiconductors and insulators is quite conventional. In insulators the forbidden gap is broader, and consequently they are bound to conduct electricity at higher temperatures when the thermal agitation of atoms is particularly intense. Theoretically it is correct, but short of melting them insulators cannot be brought to such high temperatures.



Models of metal, semiconductor and insulator. The cars symbolise electrons; the ground floor is the ground band of valence electron and the upper floor is the conduction band

Thus, the electric properties of any crystalline substance are determined by the width of the forbidden gap, or, to put it another way, by the electron excitation energy. If we classify all materials on this basis we shall have a long continuous row: at the one end, in metals, the width of the forbidden gap is zero, in semiconductors the gap broadens gradually and becomes largest at the opposite end—in insulators.

That is why there are many free electrons in metals, and none in insulators, and the number of free electrons in semiconductors depends on temperature or illumination.

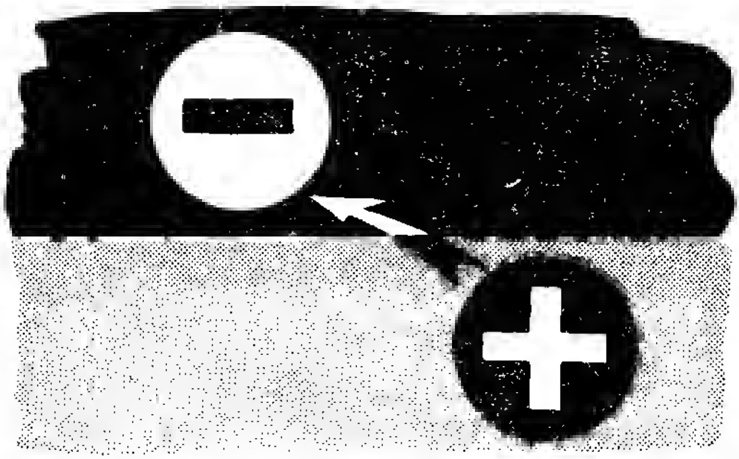
True, the electric resistance of metals also depends on temperature. But instead of becoming better conductors as temperature rises, they become worse since intensified, thermal oscillations of atoms interfere with the movement of electrons. This effect, however, is very slight: one extra degree increases the resistance of metals by a mere fraction of one per cent.

In a semiconductor a similar process occurs as the temperature rises, but simultaneously the number of free electrons increases rapidly. The net result is that resistance falls, changing scores and hundreds of times as much as in metals. We have seen why.

Now we can understand another feature of semiconductors: why for example they react differently to the light of different wave lengths. Light consists of all colours from red to violet, each of them corresponding to a definite wave length and photon energy. The shorter the wave the higher the photon energy.

If the photon energy is too low for an electron to jump into the conductivity band, the electric conductivity of the semiconductor will not change. Nor will it change appreciably if the photon energy is too high. The explanation is that a photon cannot split: it has to be absorbed as a whole, for it is a quantum, an indivisible portion of energy. Nor can an electron receive more energy than is necessary for its excitation, for the electron has to fill

only a definite, allowed level. Thus, photons with energies strictly corresponding to the "needs" of electrons can only "knock out" these electrons in quantities, increasing the electric conductivity of the semiconductor thousands or even millions of times.



MYSTERIOUS DOUBLES

UNRULY BUBBLE

As children we were fond of watching a carpenter at work. His razor-sharp axe, all kinds of chisels, a plane and other tools were always a source of delight. But the chief attraction was the level, a smooth block of wood containing a glass tube sealed at both ends. The tube is filled with water or alcohol, except for a little bubble of air looking like a transparent bean. It seemed to us that there was nothing in the tube but this bean rolling from one end to the other. As soon as the right end is lowered the bean rolls to the left. Lower the other end and the bean glides to the right.

"Well, that's simple enough," you will say. "The water flows by gravity towards the lowered end and the buhhle naturally shifts in the opposite direction."

Quite right. This simple tool will help us to understand a rather complex phenomenon.

But first another example.

Imagine a long row of taxis. A passenger got into the first one in the row, the meter clicked and off the car went. A second car moved up to the vacant place, a third filled up the vacancy left by the second, then the next drew up, until the line minus one car was again unbroken.

This event, however, can be described differently. The vacant place left by the first car shifted to where the second car had stood, then to where the third car had stood, etc., until it came to the opposite end of the row. The cars all shifted in one direction and the vacant place in the other.

You have no doubt guessed that there is a certain analogy between the carpenter's level and the taxi stand. Now let us return to electrons and semiconductors.

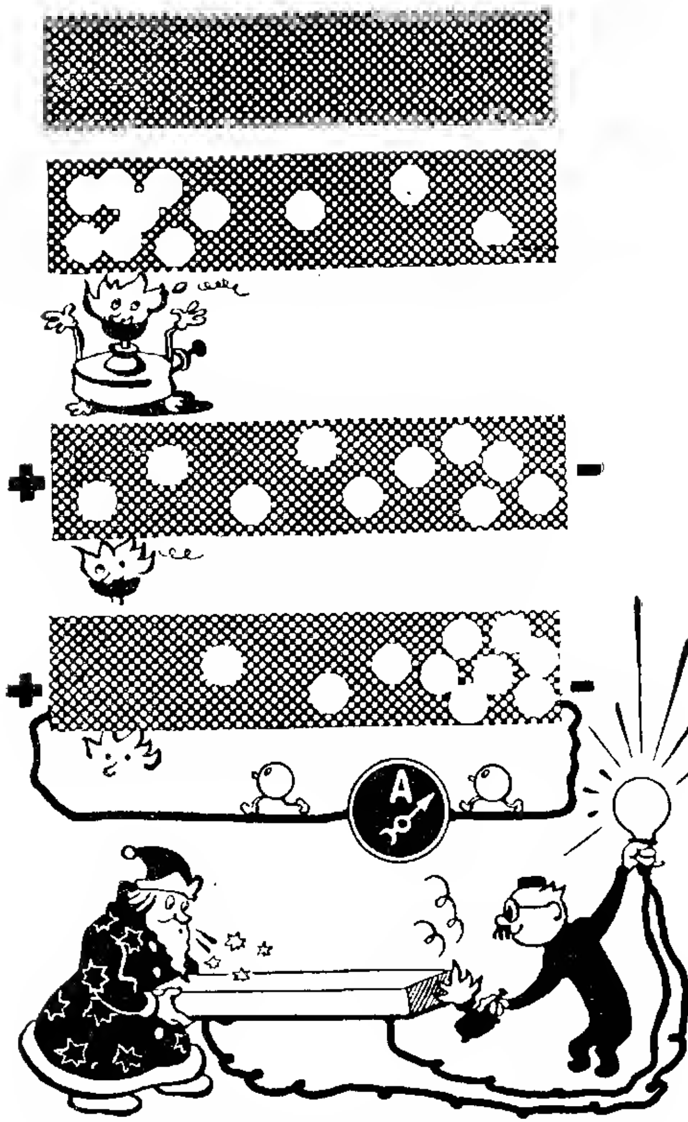
Suppose we heat one end of a semiconductor plate over a gas burner. We know that the number of free electrons increases in the heated end, but remains the same in the cold one.

Naturally electrons rush along the plate towards the cold end which becomes richer in electrons and charged negatively, while the hot end, which will lose some of its electrons, will be charged positively. There will be a potential across the plate as across the terminals of a battery. If we connect the ends of the plate, a current will start to flow in the circuit.

Our plate is a miniature power station which converts heat into electricity without machines. This electricity is called thermoelectricity because it originates from heat and the potential across the plate (when its ends are not circuited) is known as thermoelectric motive force, or thermo-emf for short.

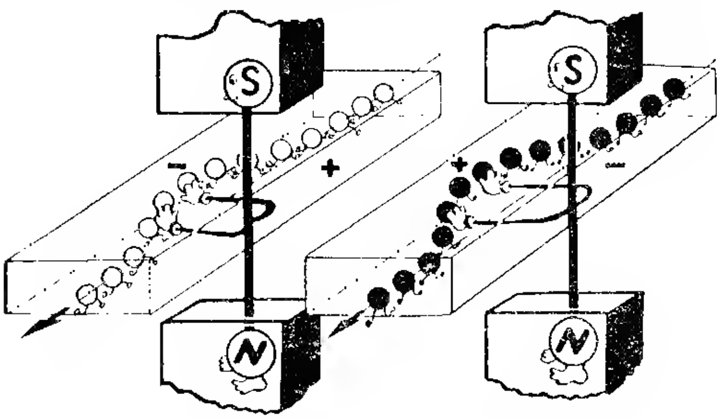
Is the cold end always negative and the hot one positive?

By no means. There are quite a few semiconductors in which the cold end is charged positively and the hot one negatively.



With one of its ends heated, a semiconductor plate becomes a miniature power station

This is certainly confusing. A rise of temperature causes an excess of electrons in the hot end and they move to the cold one. But when the semiconductors of the latter type are heated it seems that some positively charged particles appear—quanta of positive electricity as it were.



The outer magnetic field pushes current carriers towards the plate's edge

Yet it is known for certain that in semiconductors just as in metals an electric current is produced only by electrons. All the more strange is the behaviour of those semiconductors in which the hot and cold ends have their charges reversed. Incidentally, the same mysterious process is observed in certain metals.

The process defied explanation for a long time. Some physicists wonder if the Hall effect had something to do with it.

What is the Hall effect?

If a long semiconductive or conductive bar is placed in a magnetic field whose lines of force run through it, say, from the surface of one wide side to that of the other and a current flows through the length of the bar, a cer-

tain potential will arise across the narrow sides, i.e., in the direction normal to both current and magnetic field. In other words, one narrow side will have a positive and the other a negative charge.

It appears that the magnetic field deflects the current, pressing it from one narrow plane of the bar to the other, as it were. This edge acquires a charge of the same sign that current carriers have.

So in this case a current is produced by negative charges, electrons, in some materials and by their positive doubles in others.

Now what are these mysterious doubles like? It was again the modern quantum theory which supplied the answer. Our taxi stand and level will help us to understand it.

TWIN BROTHERS OF A BUBBLE

Let us recall that a current appears in semiconductors when electrons jump from the ground band into the conduction band.

Now what happens in the ground band after a valence electron leaves? We have said that each electron has its own quantum state. When the electron leaves, its state or its "place" cannot remain vacant for long. It is taken up by an electron from an adjacent atom, the new vacancy is filled up by an electron from another atom nearby, and so on. The vacancy, or the "hole" as it is called, moves through the substance.

A "hole!" A strange word to choose for a term. But why should scientists always coin such words like nucleon, neutrino or positron to name the phenomena they have discovered? Quite often the language of science can be enriched by plain words, far removed from any learned sphere. As they enter the world of science these words acquire new meaning.

We have mentioned electron energy levels which are actually not "levels" at all in the physical sense of this word.

but a measure of electron energy. The "field" in physics is not a woodless space or a sown plot of land, but a form of matter attributable to the special features of microparticles. A "star" in nuclear physics is not a celestial body, but a photographed cluster of rays.

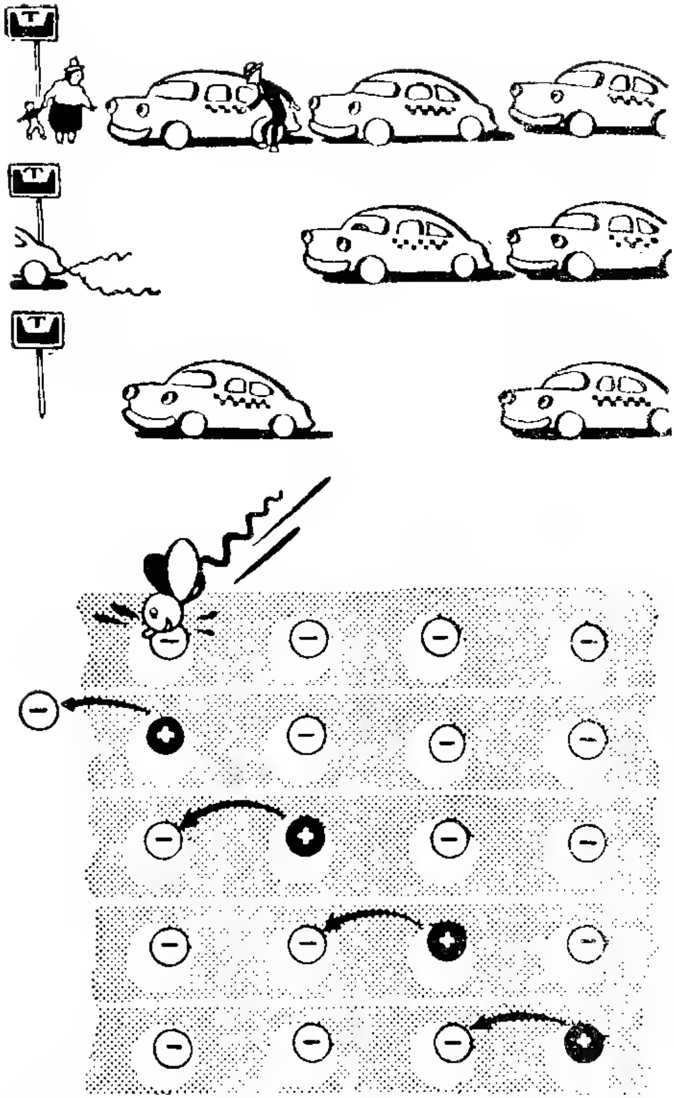
In semiconductor physics quite a few plain words have been recirculated with new meanings. Later we shall come across the "barrier layer" and the "reverse bias". Now we are discussing a "hole" which is not what the word means in everyday life. A hole is a highly complex phenomenon in the world of electrons, so complex indeed that we shall not be able to explain it at once or exhaust its meaning.

But to return to the holes moving in the substance. When a battery is connected to the semiconductor the released electrons move to the positive pole because charges of the opposite sign attract one another. And what about the holes?

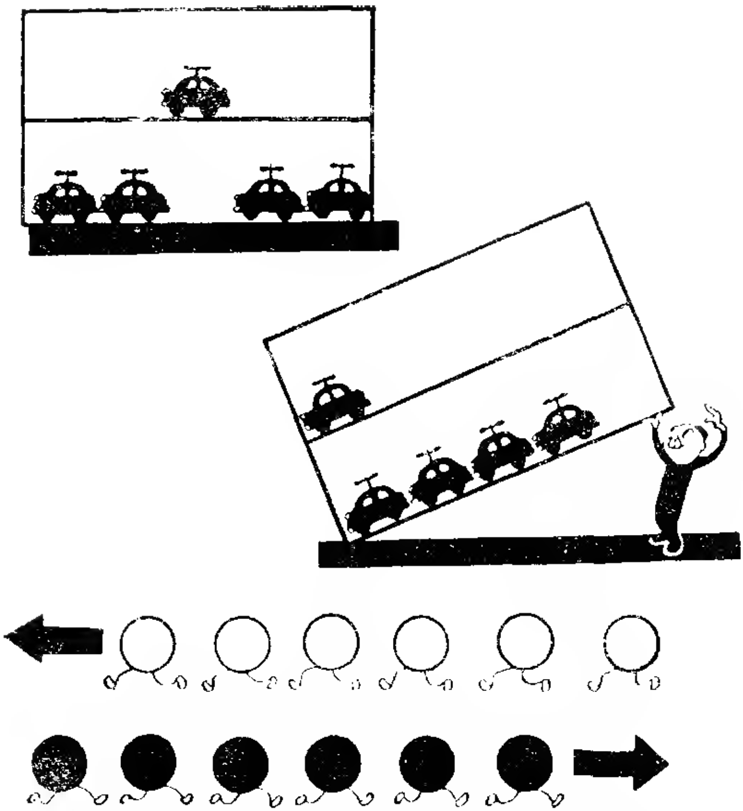
The electrons which have remained in their quantum "places" in the ground band also tend to the positive pole. But their freedom is limited. They can only jump to the vacant places next to them. They also take part in the production of the current—moving little by little to the positive pole. The hole naturally shifts to the negative pole just as the vacancy does in the row of cars.

But holes are not just vacancies, they are also positive charges. This should not be taken literally, of course. Actually a hole has no charge at all. It is simply a quantum vacancy, or to put it roughly, a space without any negative charge in the midst of such charges. Wherever holes accumulate, there is lack of negative charge, or, which is the same, there is a certain positive charge.

The behaviour of electrons within the ground band is much more complex than we have described. It involves the wave nature of these particles. Paradoxically, the electrons which behave as normal particles of negative electricity in the excitation band seem to be replaced by particles of positive electricity in the ground band.



Cars at a taxi stand move forward and the spot vacated by the first car backward. Similarly, electrons in a semiconductor crystal (white circle marked —) move towards one side while the "hole" (black circle marked +) moves in the opposite direction



Tip our model and you shall see how a current is generated in a semiconductor: the cars (electrons) move left and the vacancy ("hole") moves right

This substitution is illusory, of course. The paradox arises because we are explaining extremely complex phenomena involving the laws of the quantum theory in terms of unsuitable "classical" analogies and comparisons.

Now it is clear that our model of a semiconductor described in the previous chapter is incomplete. Let us recall

that in *this model the* ground and the upper floor of the garage designate the ground and excitation bands and the cars—the electrons. Now we should add that whenever cars appear in the upper storey, they leave holes on the ground floor.

Let us tilt our garage and all cars on both floors will roll to one side, while the holes will move in the opposite direction, just like the bubble in the carpenter's level.

The force of gravity acting on the water in the level or the cars in the garage symbolises an electric field. The lower end is the positive pole which attracts the electrons and the upper end is the negative one to which the holes move.

Thus, a current in a semiconductor can be produced by both free electrons and holes. And though they move towards each other, both electron and hole currents have, strange as it may seem, the same direction.

At the dawn of electrical engineering, more than a hundred years ago, it was assumed that a current in the outer circuit flowed to the negative terminal, as though carried by positive charges. Later electrons were discovered moving in the opposite direction. But changing the original assumption would involve redrafting the entire code of electrical laws which had been worked out by that time. Therefore it is still assumed that an electric current moves counter to the actual movement of electrons.

In semiconductors alone the conventional direction of current has proved to be real in those cases when the current carriers are positive charges, i.e., electron vacancies in the ground band.

AT A RICKETY TABLE IN A RESTAURANT

Our model of a semiconductor is, however, still incomplete. The number of electrons and holes is always the same in our model: there are as many holes on the ground floor as cars in the upper storey.

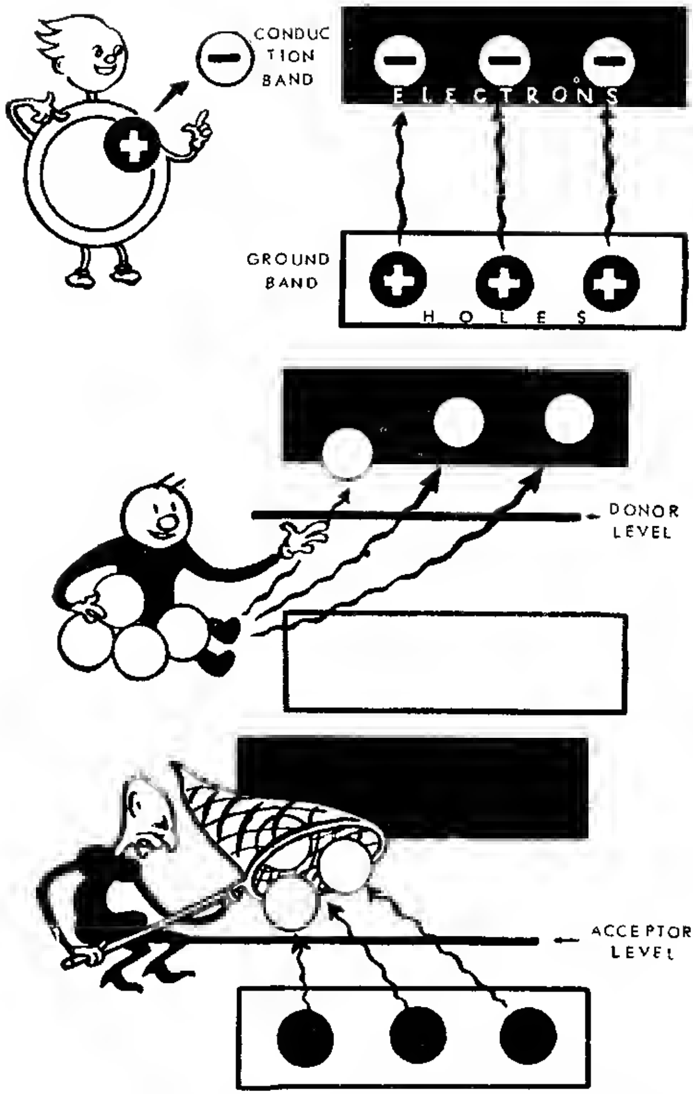
Actually, this scarcely ever happens. The number of electrons equals that of holes only in very pure "intrinsic semiconductors". It is scarcely, if at all, possible to obtain such absolutely pure materials. Semiconductors in engineering always contain impurities, which, no matter how insignificant, determine its electrical properties.

Here we approach another and probably major peculiarity of semiconductors: their sensitivity to impurities. An infinitesimal contamination, a fraction of one per cent of another substance, can sometimes sharply change the electric conductivity of a semiconductor.

The atoms of almost any impurity scattered at random among the atoms of a semiconductor either readily absorb free electrons, or part with their own—even more readily than the semiconductor itself. We shall explain why somewhat later. Now we shall merely note that an impurity sharply changes the relation in the number of electrons and holes in the semiconductor, so sharply indeed that either electrons or holes remain free. If the impure atoms capture electrons, there remain only holes, positive charge carriers, and if the "strangers" part with their electrons, it is these negative particles that become the principal, or major carriers of the current.

We should enlarge the band scheme on page 39 by adding new energy levels to the semiconductor forbidden band where there could be no electrons without an impurity.

Impurities readily parting with their electrons are called donors. Their levels can vary within the forbidden band: each impurity has its own level. If a donor level lies low, close to the ground band, this impurity will have scarcely any effect at all. To escape, the impure electrons will have to take leaps nearly as big as the semiconductor electrons. If, however, a donor level lies high, close to the conduction band, this impurity will strongly affect the properties of the semiconductor: its electrons will be able to release themselves easily by making very short jumps.



Top: an ideal pure semiconductor. Each electron (white circle) ejected into the conduction band leaves a hole (black circle) in the ground band: there are as many holes as there are electrons. In real semiconductors, however, impurities are inevitable. *Middle*: a semiconductor containing an impurity which readily parts with electrons and is therefore called a donor. *Bottom*: the same having an impurity which captures semiconductor electrons and is called an acceptor

When speaking about donors we shall mean these "influential" impurities.

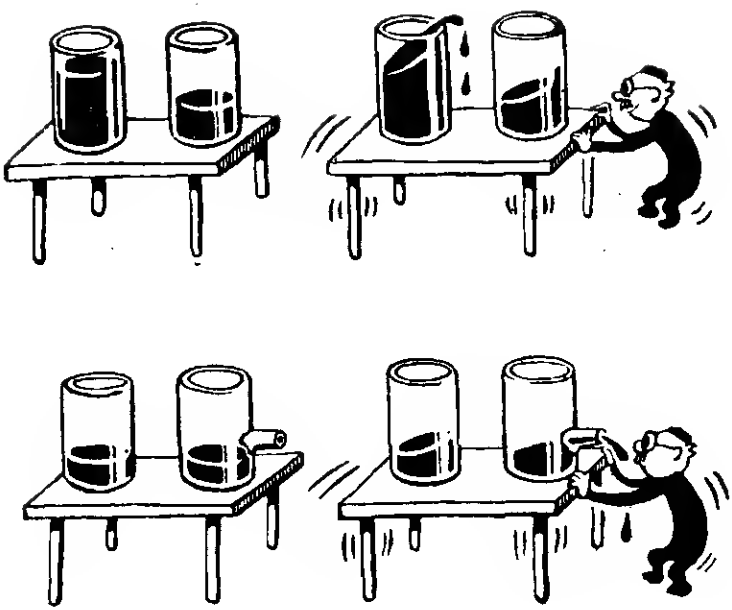
The impurities capturing electrons and producing holes thereby are called acceptors. Their levels may also vary in height. The impurity with its level in the lower part of the forbidden band, close to the valence electron ground band, is most active. Its electrons have only to make very short jumps to get to the acceptor level and be captured there, leaving behind holes in the ground band.

Now let us imagine two visitors at a rickety table in a restaurant. Both have cups of tea in front of them, but one is half finished while the other has merely sipped. The tea in the first cup will splash out only if a jolt is very strong while the tea in the second cup splashes if the table is touched ever so slightly. Similarly, the donor "splashes" its electrons more readily than does the semiconductor.

Suppose we put on the same table a coffee pot with a broken spout. Let us pour water into it until it nearly reaches the break. The water will pour through the aperture even when the table is shaken very slightly, but only a strong jolt can send it splashing over the brim. The acceptor is something like this aperture: it is easier for electrons to reach it than to jump over the forbidden band.

Usually impurities of one kind predominate in each semiconductor: either donors or acceptors. For that reason semiconductors are divided into two main types: electron semiconductors or n-semiconductors (n-type or negative conduction) and hole semiconductors or p-semiconductors (p-type or positive conduction).

A semiconductor may sometimes contain equally active donor and acceptor impurities. One kind of impurities absorbs electrons while the other gives them off. These semiconductors of mixed conduction have not been of practical interest so far: it is either n- or p-semiconductors that have been in demand. We shall soon see why.



Another semiconductor model. *Top*: an n-semiconductor (the semiconductor is the glass that is almost empty and the donor impurity is the glass that is almost full). *Bottom*: a p-semiconductor (the glass with a tap) and a pure semiconductor (the ordinary glass)

Now we have models of n- and p-semiconductors as they really are.

The n-semiconductor model can be described in this way: cars can ride about in the upper storey, while the ground floor is so crammed with cars that there is not a single vacancy. This means that there are current carriers only in the conduction band.

Now in a p-semiconductor the reverse is the case: there are current carriers only in the ground band; that is, on the ground floor there are vacancies which can drift through the garage, and the top floor is empty.

But our models are very crude and fail to reproduce many major features of semiconductors. It should not be taken for granted, for example, that there are no holes at all in n-semiconductors or no electrons in p-semiconductors. The hole-electron pairs constantly originate in thermal atomic collisions in semiconductors, and, apart from the principal (majority) current carriers—electrons in n-semiconductors and holes in p-semiconductors—there are always some minority current carriers: holes in n-semiconductors and electrons in p-semiconductors.

Free electrons and holes meet and combine, or as physicists say "recombine", becoming electrons fixed in definite places. This may be compared to the pocketing of a billiard ball. New electrons and holes appear in place of the free electrons and holes that have vanished: the pocketed balls jump out again, leaving the pockets empty.

The total amount of electrons and holes and the numerical ratio between majority and minority current carriers is constant in a given semiconductor at a constant temperature. As soon as the temperature rises the total number of current carriers increases rapidly (this is what makes semiconductors different from metals), but the ratio between majority and minority carriers either remains the same or changes a little. Electrons still predominate in n-semiconductors, and holes in p-semiconductors. This is where the role of impurities is evident.

Finally the pattern sharply changes. When the temperature reaches a certain limit an impurity exhausts its store of "reserve" electrons or loses its ability to absorb them. At the same time the atomic thermal agitation of the semiconductor itself becomes so intense that electrons escape the valence band in large numbers. Then the semiconductor ceases to be either an n- or p-semiconductor: its own conductivity caused, as we know, by electrons and holes, comes into play. This, incidentally, is one of the chief re-

strictions of the temperature range of a semiconductor. And high temperatures are, as we know from the chapter "Harnessing the Sun", quite essential in some cases.

What we have said shows once again how complex are the electron processes at work in semiconductors. In many cases, however, we can assume that only one kind of current carrier is active in a semiconductor.

Another amendment to the previous chapter is essential. In discussing the effect of heat and light on semiconductors we assumed that the changes in their "moods" are attributable only to the changes in the number of free electrons. Actually this applies only to n-semiconductors. In p-semiconductors, as is now clear to us, the number of electricity-producing holes increases when the sample is heated or illuminated.

This is why the distribution of charges is reversed in some semiconductors when one end of a plate is heated. Holes, not electrons, accumulate in excess in its cold end.

So much for the mysterious doubles.

VALLEY AND HILL

Let us return to our semiconducting plate with one end heated. The effect will be greater if two plates, one of n- and the other of p-semiconductor, have been soldered and the junction heated. An appreciable potential appears across the soldered plates. The hot ends accumulate opposite charges, and by linking them we make a circuit in which the currents coincide in direction and intensify each other. This is how thermels and thermopiles are made for obtaining electricity direct from heat.

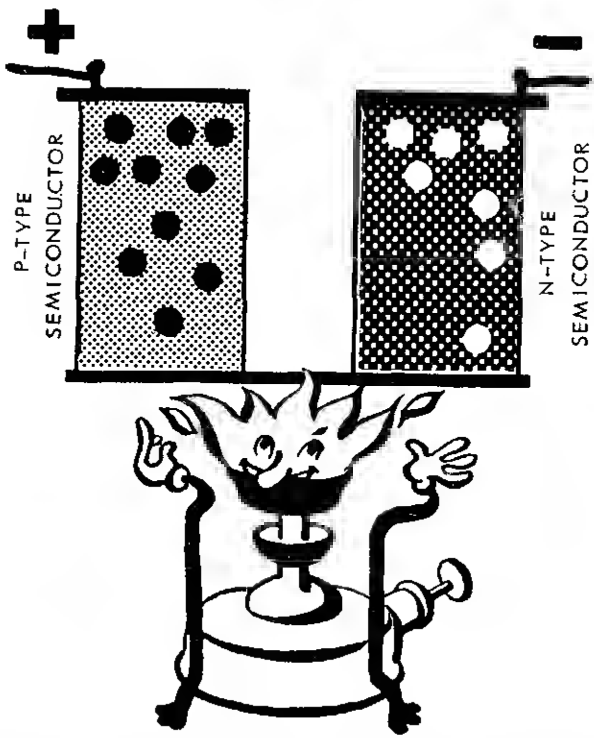
Now what will happen if we do just the opposite: connect the ends of a thermel to the terminals of a battery? The junction will either heat or cool depending on the direction of the current.

From childhood we have known electricity to produce heat in a conductor. But cold?

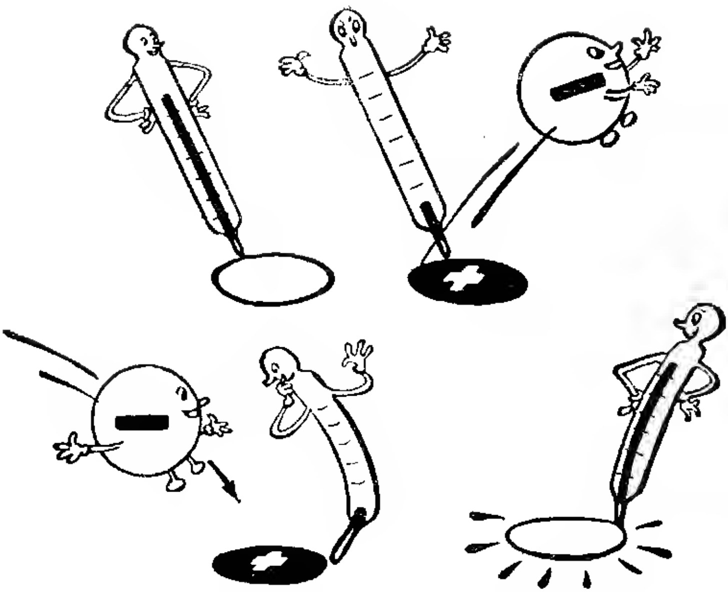
Yet now we can easily understand where the heat in the junction comes from and why it cools in other cases.

We know that an electric current in any plate is a flow of particles: of electrons moving to the positive terminal in the n-semiconductor and of holes moving to the negative terminal in the p-semiconductor.

Thus, the particles will either move to meet each other, towards the junction, or away from each other, towards the



This is how the thermel works: two plates of different p- and n- semiconductors are soldered to a metal link. When the junction is heated both holes and electrons move to the cold ends of the plate across which a fairly large potential thus originates



Disengaged, the electron absorbs a certain energy and makes a hole. The energy is released when the hole and electron recombine

ends, depending on the way the battery is connected. Figuratively, we can say that the junction either lowers with respect to the ends and the charged particles roll into this valley, or the junction rises and the particles scatter down both slopes of the hill.

Suppose electrons and holes move towards the junction. An electron shoots through the junction and into the p-semiconductor. It immediately collides with a hole and falls into it as into a billiard table pocket. Fixed at a definite spot, the electron neutralises the hole.

But a certain amount of energy has been consumed to release the electron in the n-semiconductor. Nor has the hole originated in the p-semiconductor without any energy

consumed. Finally, both gained a certain amount of energy as they moved among the atoms. All this energy is released as heat when the two combine.

Just like a heater coil the n- and p-semiconductors are heated, of course, by current and additional heat from the hole-electron recombination is released off the junction.

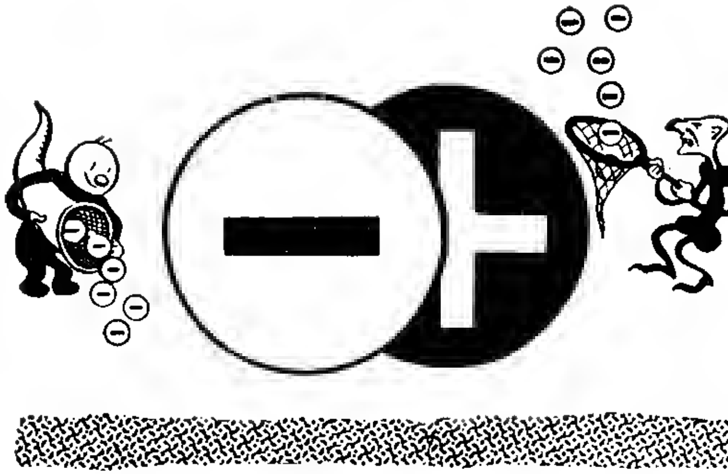
One electron after another "falls" into a hole and the junction heats more and more. This is what occurs when the current is directed from the p- to n-semiconductor. (It will be recalled that in engineering the current is assumed to move with positive charges—holes—in the present case.)

Now let us imagine that the current of the battery is directed from the n- to p-semiconductor. Then the hole-electron pairs are created, not annihilated, at the junction. From the ground band of the p-semiconductor the electrons fly to the upper storey, to the excited band, leaving holes behind.

Once created, these particles roll downhill, and new particles originate instead. Some energy is consumed in the production of each pair. Where can it come from? Partially from the current heating the semiconductor and partially from the heat of the semiconductor itself. As a result the junction cools. The cold junction naturally begins to absorb heat from the environment.

Let us make a new circuit of three soldered plates, using two plates of the same type of conduction at the ends with one plate of the opposite type in the middle. No matter how we connect the battery, the current will be directed from the p- to n-semiconductor in one joint and the other way round in the other. This means that when one junction cools, the other heats. The heat is pumped from one junction to the other.

Needless to say these peculiarities of semiconductors offer many opportunities for building heaters and refrigerators.



ONE IN A THOUSAND MILLION

SINKING BARRIERS

Surely you remember school experiments with communicating vessels? If the water level is higher in one vessel it flows into the other until the levels become even. If the water is replaced with gas in suitable vessels, the gas flows until the pressure is equal. Finally, vessels containing different gases can be connected and the gases will mix until distribution is uniform.

Semiconductors are vessels of a kind, with electrons or holes instead of gases. Suppose we connected n- and p-semiconductors. In one of these "vessels" there are by far more electrons and they will certainly rush into the other. Now, in the latter there are many more holes which will shoot in the opposite direction.

But here the analogy with the communicating vessels ends. Neither electrons nor holes will distribute uniformly

over the entire volume of both semiconductors. The electrons entering the p-layer will be captured by acceptor atoms close to the border. And the holes entering the n-layer will immediately be filled by donor electrons.

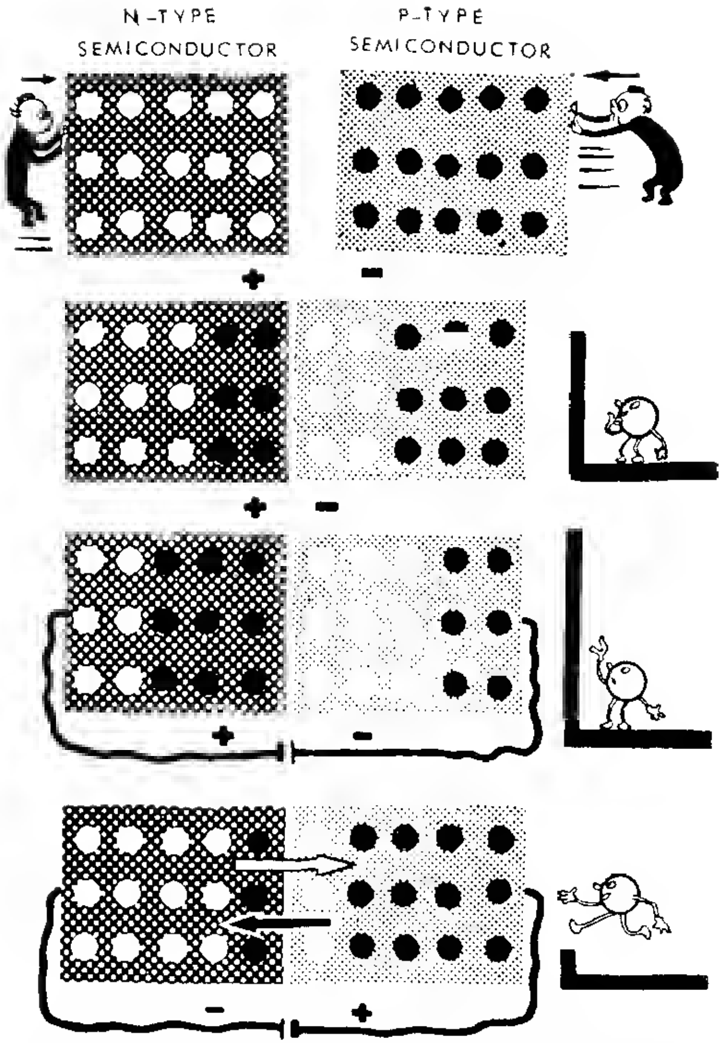
The semiconductors exchange charges, as it were, and as a result a charged band springs up in both layers bordering on the junction: a positive band (electron-deficient and hole-rich) in the electron semiconductor, and a negative band (electron-rich and hole-deficient) in the hole semiconductor. These borderland charges induce an electric field which arrests any further transition of electrons and holes—keeps them off the border.

The more of these charges the stronger the field they induce, until this field counterbalances the drive of electron and hole transitions, and a contact potential is established across the semiconductors. This potential is like two high barriers which neither electrons nor holes can clear. And since electrons and holes travel two different roads—moving in different bands—each road has its own barrier.

Now let us imagine that a battery is connected to our semiconductors: the negative terminal to the p-semiconductor and the positive terminal to the n-semiconductor. In other words, the external field from the battery intensifies the internal one.

As a result the barriers become higher, still less accessible to electrons and holes, and no current flows across the border.

Suppose now the battery is connected the other way round: the positive terminal to the p- and the negative to the n-semiconductor. The external field now acts against the internal one, weakening or neutralising it. The barriers lower or even vanish altogether, and the electrons and holes cross the border freely: a current flows unimpeded.



As n- and p-semiconductors come in contact they exchange charges, and a barrier layer passing the current in one direction originates between the two semiconductors. In engineering it is assumed that a current flows in the direction of positive charges, holes in our case. Therefore a black arrow in our sketch points the direction of the current

In other words, a special barrier region arises in a n-p junction: an electron-hole layer passing currents only in one direction.

There are few moving charges in this layer: the electron and holes have changed places and become fixed on the impurity atoms. Therefore, the layer has a high electrical resistance and is called the barrier, or depletion layer.

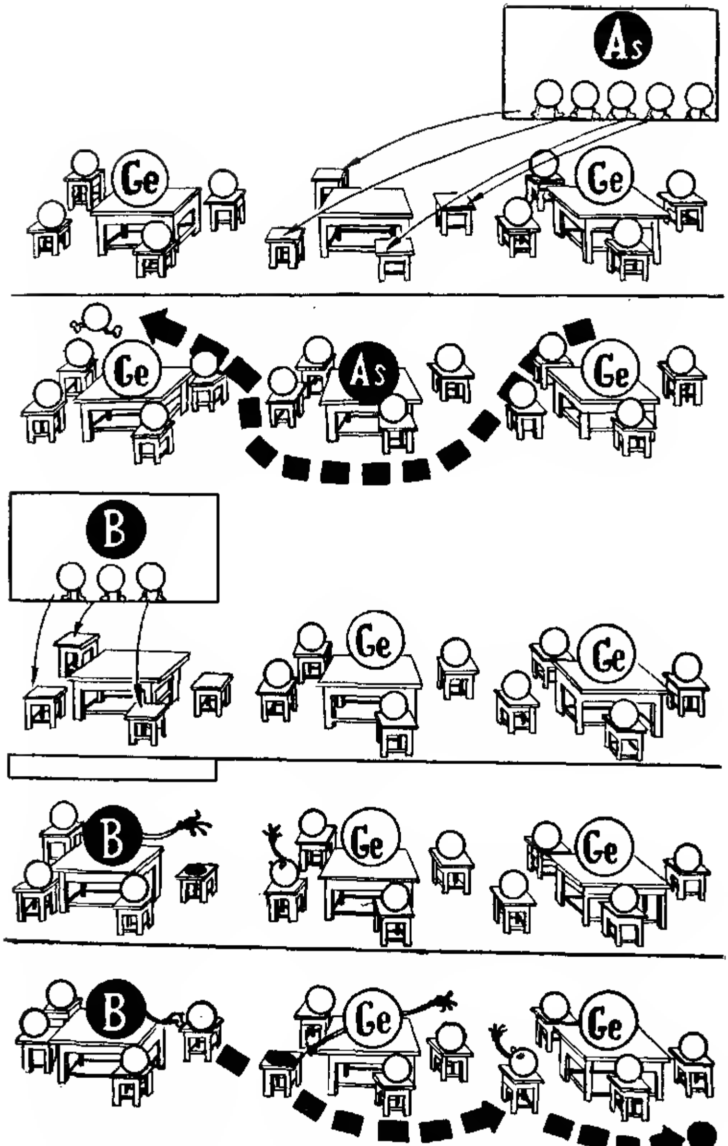
If the external field intensifies the internal one and keeps free electrons and holes off the border, the width of the barrier layer increases and its electrical resistance grows higher. The device is then said to be biased in its high-resistance or reverse direction. If the external field weakens the internal one, the barrier layer becomes narrower, its resistance falls, and the device is said to be biased in the low-resistance or forward direction.

If an alternating current source is connected to our device instead of a battery the barrier layer pulses, expanding and shrinking in turn. The electrons and holes run to the border, producing forward current, and then scatter away, forming "no-man's-land", a non-conductive layer. Thus the device pair can be regarded as a wonderful electrical vent, a rectifier of current.

"THE FIFTH MAN OUT"

The production of barrier layer conduction essentially depends on the impurities which determine the type of conduction. Let us see why some impurities capture electrons while others readily part with them. The underlying principle is manifested especially graphically when impurities are added to the most common semiconductors, germanium and silicon.

Both belong to the fourth group of Mendeleyev's Table, that of carbon, and like carbon are tetravalent. This means that the outermost electron shell of the atom of germanium (silicon) has four electrons: four hands, so to speak, by which it can hold on to its neighbours. The crystal



Different impurities—bore (B) and arsenic (As)—produce either free electrons or holes in germanium (Ge)

lattice of any of these elements is built so that each atom is connected with four neighbours.

Now suppose an atom of some substance of the fifth group, of say antimony, arsenic, phosphorus or bismuth, with five electrons in the outer shell, has entered the lattice of germanium instead of one of its atoms. Four of the stranger's five electrons will immediately link up with the adjacent atoms of germanium, while the fifth will be the "odd man out", so to speak. It will escape from its atom even if the external effect of heat or light is weak. Such "odd electrons out" determine the electron conduction of the crystal. Therefore, such impurities are donors.

But what will happen if an atom of a trivalent element, say indium, gallium, aluminium or boron from the third group of the Periodic Table gets into the lattice? Such an atom will lack one electron, and so it will take it from one of its neighbours, making a hole there. We know why the neighbour electron will readily jump over: it is much easier than getting free altogether and passing into the conduction band. And so the holes in the neighbouring atoms will render the crystal with the hole conductivity. Consequently, such impurities are acceptors.

Donors and acceptors can also be represented in this way.

Let us imagine many tables in a large hall with four chairs around each table. Five people approach a table. Four sit down and the fifth goes off to look for a vacant seat. Just like an extra "electron", he easily parts with his "atom".

On another occasion three sit at the only table in the hall with one seat unoccupied. One of the company sees a friend at a table close by and invites him to join them. Then another visitor who has been sitting by an open window moves to the now vacant seat. A fresh-air fiend walks over and takes the seat by the window. Now his former seat is unoccupied. In short, the "hole" went roaming all over the place.

Now suppose we deliberately make up companies either of five or three. Then we shall have either excess "electrons" which will shift from seat to seat, or "holes" filled up again and again.

This is what is actually done: either a donor or acceptor impurity is introduced into germanium depending on whether an electron or hole semiconductor is needed.

Sometimes it is enough to introduce one impurity atom for a hundred million or even a thousand million atoms of germanium to bring about a sharp increase or decrease in the electric conduction or even its reversal—n-conduction instead of p-conduction or vice versa. Such is the sensitivity of germanium to impurities!

The conduction of germanium can also be changed without doping. Heated up to 800° C and then quickly cooled, germanium will change its n- for p-conduction. Heated to 500° C and then let to cool slowly for about a day, it will regain its n-conduction.

The probable explanation is that a copper impurity, always to be found on the surface of the crystal, gets inside during the heating, while annealing brings it out and its effect weakens. Besides, rapid cooling after intense heating can produce dislocations in the crystal lattice which can act as impurities. After annealing, less intense but prolonged heating and slow cooling, these dislocations vanish. Something along these lines can be observed, though not so distinctly, in other semiconductors.

If the way to determine and control the type of conduction is known, it is not difficult to select a suitable pair for a rectifier which will pass a current only in one direction.

EXTENSION OF A SUNRAY

We must admit that the expression "only in one direction" is probably too strong. When the rectifier is biased in the reverse direction, a certain current still flows

through it. Apart from the majority current carriers, each semiconductor has—remember?—minority carriers: holes in an n-semiconductor and electrons in a p-semiconductor. They originate in atomic thermal collisions, as we know, and vanish rapidly as they meet with their antipodes (holes with electrons and electrons with holes). And yet a certain amount of them exists all the time.

The minority current carriers are on the other side of the invisible barriers and they easily roll down them. This reverse current is usually very weak. And the weaker it is the better the rectifier.

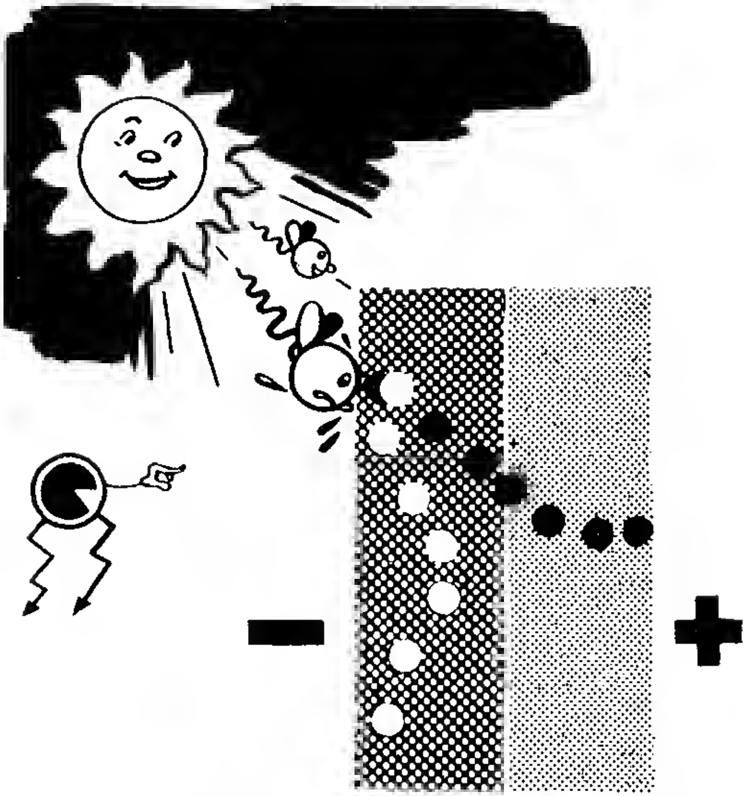
But there are instruments in which the minority current carriers come to the fore. These are semiconductive photocells transforming light into electricity.

In design they are quite similar to hard rectifiers: two semiconductors of opposite types with a barrier layer between them. This is why they are called barrier-layer cells.

In purpose, however, they differ from rectifiers. Their barrier does not lower and the majority current carrier cannot get through the barrier layer. But instead many minority current carriers arise—much more than in a rectifier—and this is on what the energy of light is spent.

Let us imagine that our two-layer semiconductor has an electron layer on its left side and a hole layer on its right. An electrode, a metal plate with a wire attached, is connected to both.

Suppose light falls on the electron layer. Quanta of light or photons hit the semiconductor atoms, give up energy to them and pry off outer electrons, thereby creating holes. Then the pairs immediately depart. The electrons, the majority current carriers in the n-semiconductor, cannot go to the right, towards the barrier layer, and so they turn to the left, to the electrode. The holes, the minority current carriers, hurry to the right, into the hole layer, and to the other electrode. Thus the incident beam of light



A semiconductor photocell consists of two different semiconductors with a barrier layer between them. Holes and electrons collect on the opposite sides of the barrier. Connect the semiconductors and a current will flow through them. *Left*: the semiconductor photocell you have seen in the previous sketches

gives rise to two streams of charges: one moves backward to meet the beam, while the other continues with the beam in its forward run.

As a result the left electrode is charged negatively, and the right one positively. The resultant potential at its high-

est (when the circuit is cut) is known as a photoelectric motive force, or photo-emf. Connect the electrodes with wire and you will have a current.

A phototube can be designed differently—so that light falls on the hole layer. In this case the electrons will continue with the sunray, for they are the minority current carriers in p-semiconductors.

ELECTRON "SYRINGE"

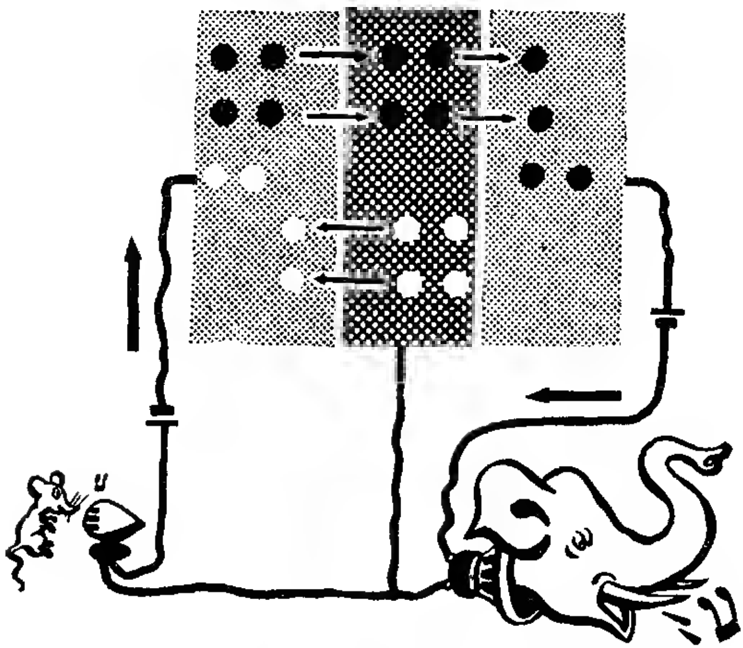
Let us now place one n-semiconductor in between the two p-semiconductors. The combination will be something like a double rectifier with two electron-hole transitions. Connect each of these transitions into a circuit in which one of them (say, the left-hand one) will be at forward bias, as is shown in the drawing, while the other (the right-hand one) at reverse bias.

Electrons and holes flow freely towards each other through the left electron-hole transition. The electrons run to the left and the holes to the right. It is the latter that are of importance in this case.

As soon as they enter the n-layer in the middle section they become minority current carriers. Therefore they can move on unimpeded through the right-hand transition where they roll easily down our imaginary barrier. Consequently, as soon as they leave the left-hand section they are immediately drawn into the right-hand section, travelling as they are from one edge to the other.

The holes produce in fact a reverse current through the right-hand barrier transition—not a weak current, however, as in the usual rectifier, but a strong current, since the left-hand transition "injects" fresh portions of holes. In this respect this instrument resembles a barrier-layer cell. In the latter the current, as we know, is also produced by minority carriers which, due to the light, spring up in abundance. In the present case these are contributed by the left-hand electron-hole transition.

True enough, some holes are wasted in the middle electron layer as they collide with free electrons. But the material and thickness of the middle layer can be selected to reduce the loss to the minimum. Then nine-tenths or even more holes will reach the end of their journey.



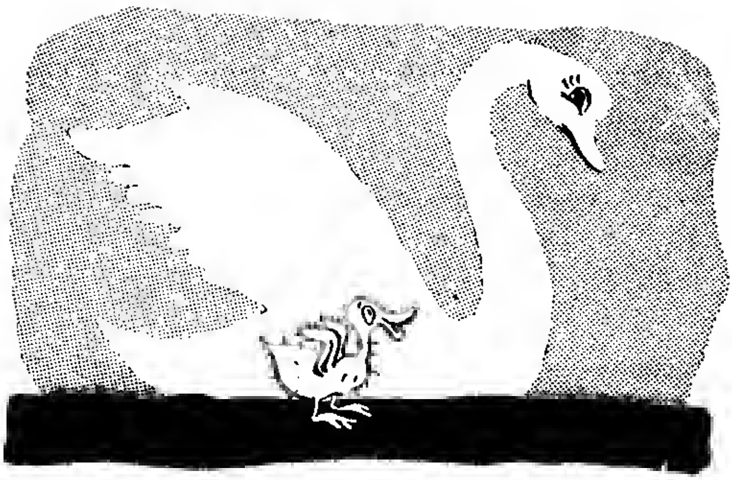
A semiconductor amplifier can turn a mouse's squeak into an elephant's roar

This means that the current in the right-hand circuit will change by practically the same value as in the left-hand one. But the circuits themselves can be different. Suppose the resistance of the left-hand circuit is low and that of the right-hand one is high. Then even the slight voltage oscillations in the left-hand circuit will bring on tremendous ups and downs in its right-hand circuit since

voltage equals the product of the current intensity by the resistance.

If we connect a microphone to the left-hand circuit and a loudspeaker to the right-hand circuit we shall have the simplest amplifier. The slightest voltage vibrations caused by man's voice will become strong oscillations producing a loud sound with the energy supplied by the batteries in both circuits.

Thus, apart from rectifying the current, a combination of semiconductors of opposite types makes it possible to amplify electrical oscillations.



UGLY DUCKLING OR SWAN?

THE CROWN OF THE PERIODIC SYSTEM

Situated in the south-east of the German Democratic Republic, near the Ore Mountains stretching along the border of the G.D.R. and Czechoslovakia, the city of Freiberg dates its nonferrous mining and smelting from the Middle Ages.

A new mineral, argyrodite, consisting of silver, sulphur and some impurity was found some three quarters of a century ago in this area. The mineral attracted the attention of Professor Winkler of the G.D.R. Mining Academy. An analysis suggested that the impurity was ekasilicium, predicted by Mendeleyev.

In his Periodic Table Mendeleyev had left spaces for another three elements which were unknown at that time. He called them ekaboron, ekaaluminium and ekasilicium (*eka* is "one" in Sanscrit and *silicium* is silicon, ekasilicium means next after silicon).

Four years later the Frenchman Boisbaudran discovered ekaaluminium which he named gallium after the ancient name of France, Gaul. Another four years passed and Nilson of Sweden discovered ekaboron which he called scandium, after Scandinavia.

Both latter elements were detected in rare minerals by the subtlest spectral analysis available at that time. Their properties coincided with perfect accuracy with Mendeleyev's predictions. Now only ekasilicium was lacking, this "most interesting of the missing elements" in Mendeleyev's words.

Naturally, Professor Winkler waited with great impatience for the chance to analyse argyrodite. He had the Royal Mineralogical Depot send him several pieces of the mineral for analysis with the obligation to return the remainder of the silver ore after the impurity had been extracted.

Soon Winkler realised that his efforts had not been in vain: the impurity turned out to be ekasilicium. He wrote to Mendeleyev about his discovery and the two were soon engaged in lively correspondence.

Despite the fact that the mineral containing silver was expensive, Winkler bought a certain amount of it and sent it to Mendeleyev. He wrote that he had the privilege of "contributing to the brilliant predictions" of the Russian scientist. Winkler invited Mendeleyev to visit Freiberg to see his experiments and the spot where ekasilicium had been discovered. Winkler called the new element germanium after his country.

Mendeleyev was delighted. "The discovery of germanium crowns the periodic system," he wrote.

That was a triumph of scientific prediction, of human genius. Germanium has since figured in numerous papers, books and lectures. But until recently this was where its role ended: discovered under such extraordinary circumstances and arousing widespread interest, the element seemed to be otherwise useless.

Everyone remembers Andersen's "Ugly Duckling". He looked neither like a duckling nor like a gosling. He was chased away and laughed at. Finally he strayed to an old lady's cottage in which the hen and the cat laid down the law. They believed there were only two reputable occupations in life: laying eggs, or purring and back-arching. And since the poor thing was unable to do either, he had to leave this cottage as well.

Germanium was also an "ugly duckling". It was too frail to be used for machine parts. It was a poor conductor, fitted neither for wiring nor for insulation. In short, it was the case of "neither laying eggs, nor purring".

The changeability of its electrical properties was regarded as an especially grave fault. At that time it was not known that those properties strictly depended on definite conditions and this dependence would in time open all doors for germanium.

A little more than ten years ago it became clear that germanium could be used for manufacturing rectifiers and amplifiers. A small crystal of germanium was found to be capable of replacing a frail and capricious radio valve. Before long germanium became the most fashionable element, with the exception, probably, of uranium. Rapidly gaining ground, this greyish metal (still called metal in spite of its being a typical member of the family of semiconductors) began to be produced commercially.

"We learned something sensible about electricity only after its technical applicability had been discovered," Engels wrote. The properties of germanium began to be studied in all aspects after its use in engineering had been discovered. The investigators' persistence matched its importance, and germanium has become one of the best studied elements.

The "ugly duckling" had become a swan. Neither Mendeleyev nor Winkler could suppose that the element which

had been predicted by the one and discovered by the other and which seemed to be absolutely useless for a good three scores of years would, in the present mid-century, march in state into engineering and revolutionise some of its branches.

NEW TRANSFORMATIONS

"The more perseveringly the chemists and physicists will explore silicon atoms the sooner they will inscribe one of the most remarkable pages in the history of science and engineering, as well as the history of the Earth itself."

A. E. Fersman had written these words before the semiconductive properties of silicon were studied. Unlike germanium, silicon has always played a major role in the history of the Earth and man's life.

To begin with, silicon is, next to oxygen, the most common element. Flint, quartz, sand, clay, granite and basalt consist chiefly of silicon. In antiquity flint served for striking fire. In Latin it was called *lapis cremans*, that is, stone making fire. The Latin for "silicon" itself is *silex* and hence its present name.

Man's first implements were of flint and his ornaments of quartz. Silicon has thus accompanied man throughout the ages.

But for all its diversity of uses silicon remained until recently an "ugly duckling", like all other semiconductors. Today silicon is among the "swans". It is used in radio instruments, its compounds, such as carborundum and various silicides, make up a large class of new and very promising semiconductors. And last but not least, silicon is today the principal material for solar batteries, needed, in particular, by spaceships which will carry inhabitants of our Earth to other planets.

The words said by Academician A. E. Fersman, Soviet geochemist, are apt today: exploring silicon will contribute

ever more remarkable pages to the history of science and of the Earth itself.

But one element has escaped the lot of the "ugly duckling" and has been in use as a semiconductor for more than 30 years. This element is selenium (from the Greek *selene*, the moon). Selenium was first used in rectifiers and later valve photocells. Its use was purely empirical, however; science had discovered its valuable properties by accident but could not explain its complex nature.

Another major semiconductor is selenium's eldest brother, tellurium. *Tellus* means "earth" in Latin.

Tellurium, on which thermels are now based, was regarded until recently as metal. Sulphur, phosphorus and iodine, on the other hand, were classed as dielectrics. As for the innumerable compounds which account for the bulk of semiconductors, their electrical properties were, as a rule, neglected altogether.

Today many of these "ugly ducklings" have proved their worth and become fine "swans".

ELECTRONIC "WIND" TRANSFERS HEAT

SECOND FORTUNATE MISTAKE

The history of thermels dates from Seebeck's mistake. Unknown to himself, he created the field which holds out so much promise today.

Another, no less fortunate, mistake was made a little more than a decade later.

In 1834 the French physicist Peltier made an experiment which was a direct opposite of Seebeck's. He took two plates (Seebeck's copper and bismuth) soldered the ends and passed a direct current through them. The junction either heated or cooled by 5° C to 10° C depending on the direction of the current.

This effect was even more appreciable in a bismuth-antimony junction: the temperature rose or fell by 40° C.

Well, what is so surprising about that? We say today. An electric circuit is made up of different materials. If

the heating or cooling of the junction produces a current in this circuit, the current can in turn heat or cool the junction. But Peltier failed to see this dependency and his explanation was entirely different.

The true nature of the process soon came to the surface, however: four years later Lentz of St. Petersburg, who studied Peltier's effect, modified the latter's experiment. He made a dent on the junction of a bismuth-antimony plate and put a drop of water into it. The water turned to ice and back to water whenever the current direction changed.

Thermo-emf is much stronger in semiconductors than in metals and this is why Peltier's effect is much more conspicuous. Perhaps semiconductive thermels can be used for building refrigerators?

Cold is necessary for processes in the chemical, food and other industries. Millions of tons of produce are stored in refrigerators of all kinds. Finally, cold is needed in scientific research and is vital for the steady operation of many instruments.

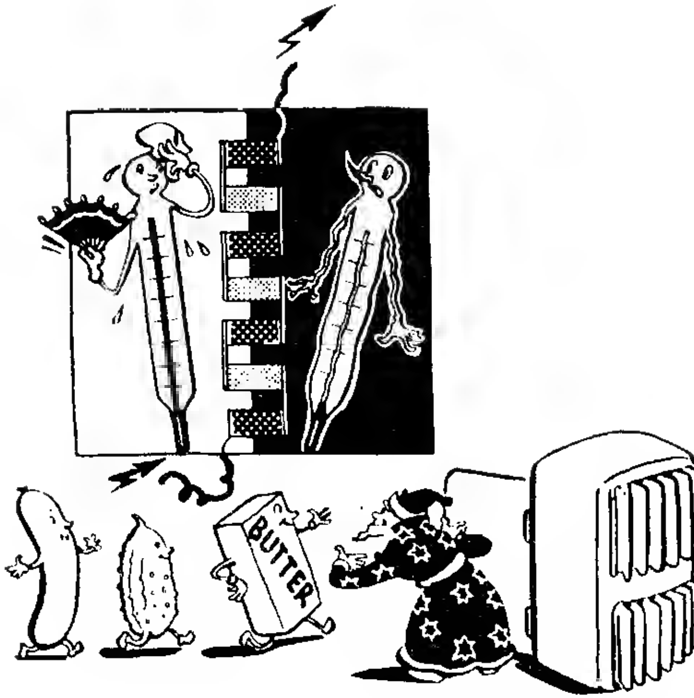
A vast amount of electric energy is spent on obtaining artificial cold. New and better refrigeration plants are essential.

While investigating thermels, A. F. Yoffe established in 1950 that semiconductor refrigerators could be more durable and simpler in design than the conventional type, and as cheap to maintain.

FOR... WHAT?

Since 1955 we have seen several experimental semiconductor refrigerators: from the first hand-made samples to modern, spacious models.

Here is a refrigerator with a ribbed back wall. There are smaller ribs inside. And between them there is nothing but thermels and a germanium rectifier. Neither motor nor coolant, nor anything else usually associated with



The semiconductor fridge looks unusual both outside and inside

refrigeration. The box cools by itself once it is plugged in.

The coolant in this case is "electronic gas", or "electronic wind" which "blows" from junction to junction inside the semiconductor plates.

To make this "wind" sufficiently strong, the thermel materials should correspond, just as in thermoelectric generators, to three principal requirements.

First, each thermel should generate the largest possible thermo-emf. Then Peltier's effect will be stronger.

Second, the plates should have a low electric resistance or much of the current will be wasted in heating them.

Third, semiconductors should have the lowest thermal conductivity possible, or else the heat absorbed in the cold junction will not come from the refrigerator box, but from the outside hot end of the plate itself.

The dependence between all these properties is expressed in physics by the quantity z characterising the thermoelectrical properties of a substance. Materials with a different z are selected for refrigerators and thermoelectric generators because semiconductors work at high temperatures in thermoelectric generators and at low temperatures in refrigerators. Naturally the thermal conductivity and electric conductivity are quite different under different conditions.

For thermoelectric generators it is sufficient for z to equal 0.001, or a somewhat larger value. For refrigerators this figure is too small, however. Owing to the persistent search for new materials (as the U.S.S.R. Institute of Semiconductors) z doubled within six years. Now it comes up to 0.002 and sometimes even to 0.0025.

If a three-stage semiconductor battery was needed before to lower the temperature in the refrigerator by 60° C —starting from a room temperature of 20° C to 40° C below zero—now this can be done with a one-stage battery.

Hence the new materials, compounds of tellurium, bismuth and antimony, or tellurium, bismuth and selenium, enable us to build small-size refrigerators which will, moreover, consume less energy. The first model of a refrigerator required nearly eight kilograms of semiconductive substance; the thermoelectric battery of the same efficiency now weighs less than a kilogram.

The design of semiconductor refrigerators is also improving. Research workers look for the most suitable form, size and number of ribs to ensure the best heat transfer. Other coolants, such as water or even ammonia, are tried.

Several of the experimental refrigerators were successfully tested in TU-104 jet liners. No rectifiers were needed for them since a direct current is available in planes. Conventional refrigerators use an alternating current and are therefore less convenient for the purpose. Besides, shock and jolts can easily damage such refrigerators, while semiconductors are fully shock-proof.

MINIATURE REFRIGERATORS

At the Institute of Semiconductors we were shown one apparatus after another, all of them powered by tiny semiconductor refrigerators. While large conventional refrigerators have some advantages over semiconductor types, small semiconductor refrigerators hold their field unchallenged. The explanation is that the efficiency factor of compression instruments decreases with the decrease of capacity.

Suppose an observatory telescope is trained on a star. The instrument must turn all the time to keep it in sight.

The star-tracking at the Soviet Union's Pulkovo Observatory is controlled by an automatic device containing a photoelectronic multiplier, light-sensitive plates arranged inside a vacuum valve with an electric tension applied across them. Astral rays hit the head-end plate and eject electrons. The beam is very weak, however (since the ray which caused it is weak). The electric field accelerates this beam and sends it to a second plate. The fresh electrons, escaping in greater numbers, hit a third plate. The process is repeated until the beam is amplified thousands of times. As the star moves the telescope's lens receives less light and this is detected by the photomultiplier switching on the telescope star-tracking mechanism.

The reliability of the photomultiplier increases at lower temperatures, and a semiconductor microrefrigerator encasing the photomultiplier enhances the sensitivity of the entire device.

Photomultipliers are also used in electronic-optical transformers for "seeing in the dark". The infrared rays emanated by warm bodies are converted by a photomultiplier into a beam of electrons which is then amplified and flashed on a screen. Here, too, the operation of the entire device, and hence the distance of observation, depend on the temperature of the photomultiplier.

The multiplier is also used in archeology. The instrument detects the radiation of carbon C^{14}, establishing thereby the age of archeological evidence. A special semiconductive cooler increases the sensitivity of this technique at least 50 times.

In nuclear physics the photomultiplier detects elementary particles; the cooler increasing the accuracy of measurement 100 times.

All these results are obtained by cooling instruments by merely 20° C to 30° C.

Sometimes photomultipliers have to descend deep underground. Readers will probably have heard or read about radioactive coring, a remarkable method of prospecting whereby a sensitive instrument is lowered into a bore to determine natural radioactivity which yields information on the composition and age of rocks and the presence of minerals.

In deep bores the temperature is too high for the normal operation of the photomultiplier. This is where a microrefrigerator comes into play: it can be lowered into the bore along with a photomultiplier.

UNUSUAL PLASTER

A patient is being prepared for an operation in a way that might have seemed impossible, absurd and harmful just a short time ago. He is narcotised and immersed in a bath of icy water until the temperature of his body falls to 24° C or 25° C. Once it was believed that heat alone was a surgeon's ally. But now it is recognised that in some

cases cold may be his best assistant. All living processes slow down in a cooled body and the patient has a better chance to pull through.

Unfortunately, the human body often resists this artificial cooling and develops a fever. Special medicines are administered to keep down the metabolism and remove this resistance. But these sometimes prove ineffective.

Should an operation without hypothermy (as the process is called) be risked in such cases? Until recently doctors had no alternative. But now there is a method of internal artificial cooling.

The patient is not immersed, but is narcotised on the operating table. An artery is opened and the blood passed through a cooling coil back into the body and thence to the brain. As a result the activity of the brain is arrested and the organism cannot resist the lowering of the temperature.

You have guessed no doubt that it is a semiconductor refrigerator that does the cooling in this case: simple and reliable, it permits accurate temperature control by changing the intensity of the current in the thermels.

This is only one of the many duties it performs in medicine. Other applications are even more striking: for example, a refrigerator is an inseparable aid to a person who has undergone the Filatov "tubed flap" operation.

A piece of skin from the patient's stomach is often used for a facial plastic operation. The skin is not cut off altogether, however, but rolled into what is known as a tubed flap to be grafted on the patient's hand. When the flap grows to the hand it is cut off from the stomach and the loose end is implanted onto the patient's face. The patient has his hand bandaged first to his stomach and then to his head. When the flap grows onto the face it is cut off the hand and the final operation follows. This method yields much better results than when the skin is transplanted directly.

The "migrating tubed flap", proposed by the Soviet scientist V. P. Filatov, has won recognition throughout the world. It may happen, however, that the blood vessels of the patient's hand cannot feed a large strip of skin. Now suppose the temperature of the strip is lowered by 10° C or 12° C. Metabolism will then be less intense and the blood feeding quite sufficient.

A miniature semiconductor refrigerator used for this purpose has the form of a tube weighing, together with a tiny silver-zinc storage battery, less than a kilogram.

The same wafer-shaped refrigerator can be used as a medical plaster. Certain skin diseases such as lupus and eczema can be cured by cold, provided the treatment is long enough.

Another use of a microrefrigerator in medicine. Sometimes no accurate diagnosis is possible without a special microscopic study of a tissue section. The device for obtaining such sections is known as a microtome; it is essentially a scalpel and a table cooled from below.

Until recently carbon oxide from a 100-kilogram cylinder was used for cooling. Apart from being inconvenient, this method is expensive and, what is worse, defies proper control, which may lead to the destruction of the cooled tissue. A new semiconductor device already in production at Soviet enterprises is free from all these defects. Incidentally devices of this kind were on show at the Brussels World Fair in 1958.

Besides improving and facilitating histological investigation, the simplicity and convenience of the new device permits its use in rural hospitals or sometimes even in field conditions.

A STREET HEATS A HOUSE

It was said in an article entitled "French Cold in the U.S.S.R.", published in the French magazine *Science et Vie*, that Soviet scientists are leading the world in study-

ing and applying the effect discovered by the Frenchman, Peltier.

Soviet investigators were naturally pleased to read this article, though its title is not quite accurate. The Peltier effect produces both cold and heat. When some thermal junctions cool others are heated. Once the direction of the current has changed, the junctions are reversed: the "hill" becomes a "valley" and the "valley" a "hill", the degree of heating or cooling depending, as we have seen, on the intensity of the current.

This property of thermels is used whenever temperature has to be controlled accurately. It has become possible, for example, to recalibrate thermometers. Formerly, only a few points corresponding to the melting and boiling temperatures of certain chemicals (say the melting of ice and the boiling of water) were marked off on the thermometer scale, the interval being divided into equal lengths, or degrees.

But the inner diameter of the capillary for mercury is not strictly uniform. There should be more degrees where the capillary is thicker and less where it is thinner. Yet such calibration was impossible under the conventional method and so the readings were not as accurate as they could be.

Semiconductive devices obviate this defect. By smoothly changing the intensity of the current the temperature can be raised or lowered by a tenth of degree within a wide range from +60° to —20°C. And if thermels can change the temperature at will they can also be used for maintaining a constant temperature.

A geophysical upper-atmosphere rocket almost invariably has a photoresistor to measure the intensity of the solar infrared radiation. The sensitivity of this instrument strongly depends on temperature. Therefore it is placed in a glass-topped box three or four centimetres in size and weighing 150 grams. This semiconductor thermostat maintains a constant temperature (in the range of, say, 20° C)

accurate to within 0.1° C, even if outside an arctic cold alternates with a tropical heat. Heat-sensitive radio parts are encased in thermostats of the same kind.

The ultrathermostat is even more accurate: the temperature in it changes within 0.001° C.

There is also a portable thermostat—for storing medicine. Cold will keep in its ribbed case as long as the storage battery inside lasts.

We can even imagine an ordinary living-room as a thermostat. Semiconductive batteries will heat it in winter and cool it in summer—always keeping a pleasant and healthy temperature.

A research team at the Santekhnika Factory in Moscow has recently designed a device of this kind. The device is a smallish perforated box with a switch. A turn of the switch to the right starts a stream of warm air flowing from the box, and a turn to the left makes the stream cool. The stream comes from a fan inside blowing the air past the thermal junctions, either heated or cooled, depending on the direction of the current.

The second group of junctions is located on the other side of the box. The device is only an experimental model. Actually, these junctions should be placed out of doors. Then the installation will pump excessive heat out of the rooms or will pump in some heat from outside. Even in deep winter the outside air could be used for warming a house.

We have been used to the fact that heat is transferred from a hot to a cooler body: the warmer walls of the house should warm the adjacent air outside. But here it is the other way round: the house absorbs the heat from the cool outside air. Like a waterfall flowing upward! In our case a thermoelectric battery is a thermal pump. Unfortunately though the current also heats the thermels themselves, producing joulean heat which conventional electric heaters produce. But since thermels pump as much free heat from outside they are at least twice as efficient.

Of course, it would be even cheaper to take all heat from outside. Then the consumption of electric energy would be insignificant. But this is impossible. What is possible is to increase the share of free outside heat by better thermels. Scientists are of the opinion that thermels will soon be able to draw not a half, but two-thirds of heat from the outside air.

Ordinary running water may also serve as a source of additional heat. The Santekhnika Factory has designed a device based on this principle: one group of junctions is located in the room, while the other is fixed to a water main.

In due time thermopiles will perhaps oust the conventional devices used for heating, cooking and industrial purposes.

A MIRACULOUS FILM

The suspended bulb had no heater coil, only two lead-in wires sunk right into the glass, yet water in the bulb was boiling.

This was one of the most fascinating exhibits at a Czechoslovak Glass Show. The sparkling bulb drew the puzzled question: "Why is the water boiling?"

This bulb reminded us of the experiment we had seen at the State Optical Institute in Leningrad. It was also puzzling.

Two silvery rings with wires attached were put on a glass of water. The glass was smooth and transparent and it was not clear what the rings and wires were for. Then the plug was put into a socket and soon the water was boiling.

It looked like a hoax, with rings, wires and plugs just for the sake of appearance, while the glass was actually heated from below. But there was nothing below except for a heat insulating layer to prevent the glass from damaging the table.

We learnt that two transparent layers had been deposited over the glass, one on top of the other: a very thin (3-micron) film of semiconductive material, stannic oxide, and another of insulating silicon-organic varnish. Heated by electricity stannic oxide heats the glass, while the silvery metal rings act as electrodes.

The glass heated so quickly because the film of stannic oxide had been melted into it at a high temperature, thus making an ideal thermal contact. No other heater can be pressed so tightly. The efficiency factor for conventional electric heaters varies from 30 to 40 per cent, while in this case it is 90 per cent.

The Self-Cooker Pan and Self-Boiling Teapot are no longer figments of imagination. A boiler attached to a tap has already been designed: it consists of two glass tubes, one inside the other, with water flowing between them. Once the plug is in the socket water begins to steam.

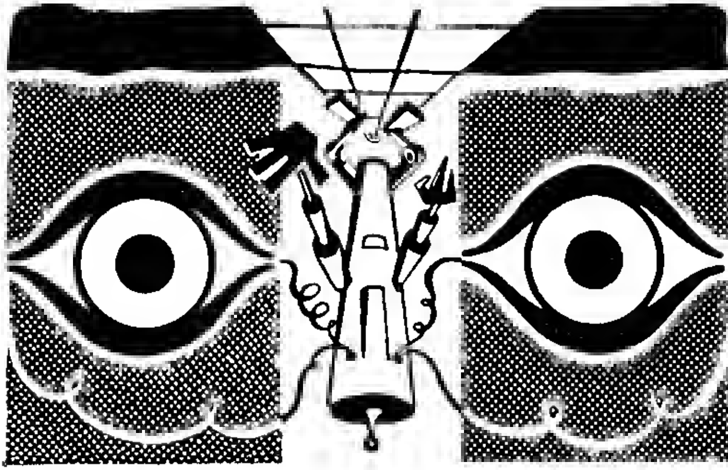
A film of stannic oxide will in time replace the conventional, cumbersome and expensive heaters in electrolytic workshops, and will enable the chemist to watch any reaction, for the uniformly heated vessel remains transparent. The freezing and sweating of the window glass in planes, trains and motorcars will be a thing of the past. Windows with a special filmed glass will heat houses, and consume little electric energy in the process.

So the invisible film heater has definite advantages, and it can perform other duties.

The film, for example, can detect charged particles in a cloud chamber, an instrument used in nuclear physics. While passing through the chamber these particles leave tracks behind and hit glass walls. Unless removed, their charge will affect other particles, deflect their paths and distort the entire picture. The walls therefore are usually coated with a thin grounded film of chromium. But chromium lessens the transparency of the walls and interferes with photographing and observing the particle tracks. A film of stannic oxide has no such defect. Besides, it is a bet-

ter current conductor and so it will remove the charges more effectively.

The film can also be used for manufacturing the upper electrode of a photocell which so far has been made of metal. However thin, a layer of metal absorbs much light, while that of stannic oxide is absolutely transparent.



SENSITIVE, SHARP-EYED, VIGILANT

A THERMOMETER ON FIRE

Can one take a furnace's temperature with a thermometer?

While they are locked in the furnace no one can measure the temperature of shaft top gas, pig iron and slag, a steel specialist will answer.

Today the specialist may be right, but tomorrow....

Semiconductors are a young branch of science and engineering. But high-temperature semiconductors are even younger.

Only four years ago Academician A. F. Yoffe wrote: "Extensive and varied, the sphere of semiconductors has been investigated so little that other materials and other properties, apart from those which have already been in use, can well be expected." In particular, the scientist indicated that "semiconductors include an extensive class of

superhard refractory carbides, borides, nitrides and silicides which have been used very inadequately so far. It can be supposed that by studying them and by learning how to control their properties we shall obtain new means for solving many problems of engineering, progressing towards high temperatures and great pressures."

This road has been taken by a team of investigators headed by Professor G. V. Samsonov, and the first results are already on hand.

Pavel Stepanovich Kisly, a research associate of the Institute of Metallo-Ceramics and Special Alloys of the Academy of Sciences of the Ukrainian Republic, showed us a steel-like rod, half an inch thick and half a yard long. One end of the rod was rounded and the other had two leads.

"Here is our thermometer—not yet fit for a furnace, though," he told us.

The rod was actually a pipe of molibdenum silicide, a compound of molibdenum and silicon, with a thin core of boron carbide.

At the rounded end the core and the pipe are welded. One of the wires issuing from the other end is connected to the pipe and the other to the core. Thus we have a thermel.

When the junction is heated the cold ends develop, as we know, a potential or a certain thermo-emf. If the wires from these ends are connected to a sensitive instrument, the potential difference will show the temperature of the junction.

Metal thermocouples have long been used for measurements. Yet semiconductive thermocouples generate a considerably stronger thermo-emf, and are hence more sensitive. For low temperatures they have decisively proved their superiority over their metal competitors. At high temperatures, however, the latter still hold their own.

The most common thermopair consists of two fine wires, one of platinum and the other of a platinum-rhodium al-

loy, with a protective casing around them. The highest temperature this instrument can stand is 1,600° C.

"Our thermopair is good for 1,800° C," said Kisly. "But the chief thing is that it generates 40 microvolts per degree, that's a thermo-emf four times as high. Its measurements are as many times more accurate. Besides, it is much cheaper since it is manufactured out of common materials in a very simple way: both pipe and core are pressed out of powder and caked at high temperatures. All that is left is to weld the ends and connect the wires."

A semiconductor thermopair is already used at iron and steel mills for measuring the temperature of waste gas and hot air in the vertical canal of an open-hearth furnace (1,800° C to 1,900° C). The thermopair will no doubt be applied at machine-building enterprises to automatically control the temperature in furnaces, in the glass industry and nonferrous metallurgy and at aluminium works.

Aluminium is produced in electrolytic baths. From time to time a batch of smelted metal is let out and alumina is added. The temperature in the bath falls, but rises again as the alumina is heated and smelted. Temperature control is essential. A semiconductor thermopair in a protective casing of silicon nitride (a compound of silicon and nitrogen) can be dipped into this bath much like an ordinary thermometer into a children's bath. The thermopair can remain in the smelted metal up to 1,000 hours on end.

Finally a thermopair can be dipped in the molten steel of an open-hearth furnace. A platinum thermopair with a ferrule of quartz can be dipped twice for a minute each time. A semiconductor thermopair can be dipped for any number of times without any protective casings, provided the immersion is not too long. But investigators are not satisfied. Their ideal is to produce an instrument which can remain in metal throughout the process, registering temperature automatically. A material to encase a thermopair enable it to sustain a three-hour bath in molten steel has already been found. This material is titanum nitride (a com-

pound of titanium and nitrogen). Double the time-length, making it equal to the total smelting period—and the problem is as good as solved.

A thermometer for a blast furnace is a harder nut to crack. In the hellish flames that rage in a blast furnace the charged materials become enormously aggressive. So far only a casing of zirconium boride, a compound of zirconium and boron, has been found for this purpose. In this casing a thermopair can remain in molten pig iron for about two hours. The device can be simplified: the thermopair pipe (outer electrode) can be made of zirconium boride and then no protective casing will be needed.

But this is just the beginning. Today there is no thermometer which could be put into a blast furnace but it will certainly be designed before long.

There are fields of engineering, such as the production of hard alloys, where even higher temperatures, up to 2,000° C, have to be measured. Ukrainian scientists have designed a semiconductive thermopair capable of resisting 2,000° C to 2,300° C. The piping is made of titanium carbide and the core of boron carbide. Even more sensitive than its predecessor, this thermopair generates a still stronger thermo-emf: 45 microvolts per degree. Nor is this the limit. The same institute has designed a thermopair (of boron and silicon carbides) capable of generating a tremendous thermo-emf of 600 microvolts per degree. This is not simply a measuring instrument, but an honest-to-goodness transformer of thermoenergy into electricity. We mentioned it in the chapter "Harnessing the Sun".

BABY THERMOMETER

Signal lamps go on and off on the main control board of a power station. Without leaving the room or even getting off his seat, the engineer on duty feels the pulse of the powerful transformers.

A major sign of their "health" is their temperature. Quite recently an engineer on duty had to make the rounds, like a nurse in a hospital, and take down the readings of the thermometers which stuck out from the transformer housings. The thermometers measured the temperature of the oil in which the cores and windings were immersed.

One can still see these transformers. But side by side there are transformers without them. The engineer on duty never comes near these latter transformers, yet he is aware of all temperature fluctuations. As soon as the temperature reaches a certain limit, a signal lamp glows on his desk. The fans next to the transformer are automatically switched on. When streams of air have cooled the oil, the signal goes out.

Another group of lamps on the desk registers the temperature of the turbine and generator bearings which support the weight of the massive rotors and which turn day and night at tremendous speed. The overheating of a bearing may lead to a breakdown. This is why, even more often, the engineer on duty had to inspect the thermometers installed in the bearing housings. Now this is also taken care of: the signal lamps will sound the alarm.

But who switches on the lamps? A wire stretches from each of them. Let us follow its course. At the end we shall find a small tube sunk into the housing of a bearing or a transformer. The tube is no more than a centimetre long and less than two millimetres wide. It is a thermosensitive resistor, or thermistor, for short. The thermistor is connected to a battery and the intensity of the current in this circuit is determined by the thermistor resistance, which, in turn, depends on the temperature. A galvanometer can be connected to the thermistor instead of the signal lamp and calibrated for degrees, not amperes.

On closer inspection the thermistor proves even smaller than it looks. What might have been taken for a thermoelectric resistor proves to be merely its external shell, a glass or metal casing. On a fine wire inside, in the very

centre of the tube, we can discern a tiny nodule the size of a sharp pencil point. It is a thermoelectric resistor.

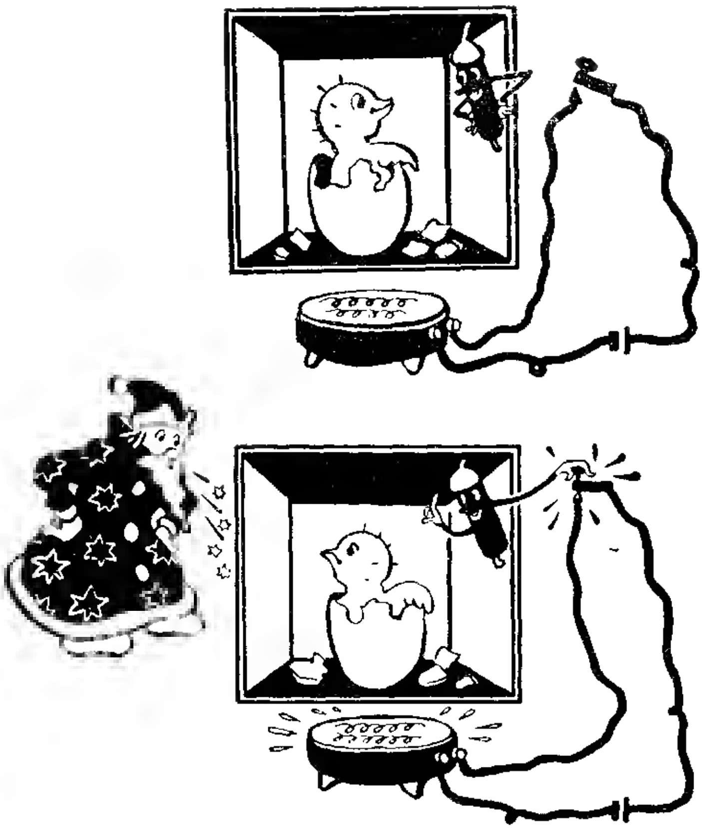
As a rule a resistor contains oxides of copper, manganese, cobalt and other metals. Such substances are called oxide semiconductors. By changing the composition of the alloy scientists impart the wanted properties to a thermoelectric resistor. Thermistors measure the temperature in a ship's cabin or a deep oil bore, prevent the icing of a plane, control the temperature in a hothouse or an incubator.

Usually these instruments resist heating up to 300° C. New thermistors of silicon nitride operating at 1,000° C to 1,300° C have been made in Kiev. True, they do not work at all at room temperatures—no more than the thermocouples described above do, for that matter. In general the high-temperature semiconductors behave like insulators below 300° C to 400° C. The moral is that different types of instruments should complement each other.

A thermoelectric resistor needs not necessarily be encased in a tube. A very thin film can be deposited over a dot-sized thermistor. This microscopic instrument is capable of measuring the temperature where the conventional thermometers would be useless—in man's stomach, gullet, or even a blood vessel.

Due to its size, the thermistor has the advantage of quick response. Needle-type thermistors have been produced in Leningrad. A semiconductive ball several microns in diameter is coated with a very thin film of glass with two lead-in wires of platinum. A galvanometer attached even shows the temperature of a green leaf almost the moment the sharp point of the semiconductive needle touches its surface. These thermometers are of much help to botanists and physiologists studying the life of plants.

Quite a few other semiconductor instruments have been designed by the U.S.S.R. Agrophysical Institute for agriculture. They reveal hitherto unknown properties of plants. It has been established, for example, that plants have their



It it gets too cold inside the incubator the thermistor immediately switches on the heating

"habits" and the plant "chooses", given the chance, the most suitable conditions for its life. An automatic system switching light on and off and connected with the plant itself has been devised. Miraculously, the plant itself does the switching, controlling the illumination in accordance with its biochemical needs. The plant has developed a "conditioned reflex".

Automation extended to other aspects of the life of plants could revolutionise agriculture.

The progress of Soviet science and engineering brings closer the time when the pressure of a button will start rain. Striking discoveries like the "conditioned reflexes" in plants are unmistakable omens. It is not impossible that even the pressure of a button will be superfluous to hring on rain: the plants themselves will take care of that. The study of semiconductors, and in particular, the designing of new automatic devises, lead to progress in that direction. Characteristically, the study of plants' habits began with the designing of a superminiature thermometer.

A "FIREMAN", A COUNTER, A MANOMETER

The design of certain thermistors seems rather strange at first glance: inside a glass vacuum tube, a sensitive semiconductive filament is surrounded by a coil which heats it. Now, why heat the thermistor? It will not register the temperature of the air. Or will it?

The fact is that it will do it, even more readily than the usual thermoelectric resistor. The heat released by the coil is dissipated in the air and the temperature of the thermistor is kept permanent. As soon as the heat absorption of the air becomes worse the thermistor gets overheated and the current increases several times. This jump ensures the switch-on of the signal instruments.

This is how a "fireman" thermistor acts. If the temperature in a grain elevator, for example, rises above the limit by even half a degree the signal system sounds the alarm.

A similar device is at work in a gas or oil pipe. Like the "fireman" it is also heated by the current, while the gas in the pipe blows by and cools it. If the speed of the gas decreases the thermistor gets overheated and the current rises. The galvanometer shows the intensity of the current and hence the passage of gas or liquid through the pipe. In other words, a thermistor in a pipeline is a gauge.

Thermistors are used in vacuum stations as well. The number of particles dissipating heat decreases as air is pumped out. Placed into this vessel, the thermistor will, therefore, act as a pressure gauge measuring the degree of vacuum.

There is a great variety of thermoresistors. Some of them are not intended to measure, control or detect. They are designed to be heated gradually at a strictly definite rate and pass an increasingly stronger current through an electric circuit.

When the potential, or voltage, applied to a thermistor is high, the free electrons receive large additional energy and transfer it in collisions to the atoms. These move more rapidly and the temperature of the body rises. The coil of an electric stove is heated in the same way.

Many electric motors require a gradual increase of the current at the start. Thermistors are more reliable than the rheostats formerly used—and they are automatic, too. As a thermistor gets heated, the current it passes increases steadily.

The larger the thermistor the slower it gets heated. A thermistor's total heating time can be established, from a fraction of a second up to ten minutes, by selecting the proper size, ranging from a scarcely perceptible speck to a plate of one or two centimetres, or if necessary by installing an additional cooling system. Thermistors are needed when several machines must start up one after another at different intervals of time.

While quickness of response is one of the chief assets of semiconductor thermometers, thermistors of the above kind are remarkable for their sometimes quite considerable time lag.

There are also thermistors which register heat at a distance, through radiation. These instruments are called bolometers, from the Greek *bole* which means a "ray". Placed at the focus of a parabolic mirror, the semiconductor bolometer can detect the heat of man's body several

kilometres away. By thermal radiation the bolometer can detect planes, ships and other vehicles from afar, even if they move with lights and engines switched off. Industrially, bolometers are used for non-contact measurement and temperature control, in the baking of ceramics, for example.

We cannot describe all types of thermistors. It is time to turn to another major field of semiconductor automation in which instruments are triggered by light and not heat.

A "SANDWICH"

An instrument somewhat smaller than a suit button was lying on the table; it was a plastic case with a round hole somewhat larger than the capital O in our book on one side and a two-pin plug on the reverse side.

One of the designers, G. A. Fedorus, a research associate of the Institute of Physics of the Academy of Sciences of the Ukraine, took the lid off the instrument and we saw a tiny, almost transparent yellowish plate of sulphurous cadmium. The plate was attached to the case with a special glue and connected to the pins.

This instrument is called a photoresistor. Darkness appears to make it an insulator, while illumination increases its conductivity millions of times. Its amazing sensitivity makes it of inestimable value for automation. It sharply changes the intensity of current in a circuit, depending on the incident light, and without fail switches on the wanted instruments.

Next to it we saw another instrument which, except for its action, hardly differed from a photoresistor. When illuminated it became a source of current. It was a valve photocell, twin brother of the silicon photocell we have spoken about. In the valve photocell there are two semiconductors with different conduction. It is a sort of "sandwich". For example, the selenium photocell consists of a hole sele-

nium layer (the "bread") and a very thin electron layer (the "butter")—with a barrier layer between.

This instrument appeared about sixty years ago. Vacuum photocells had only been known before. Imagine a glass tube (not unlike an ordinary lamp) from which the air has been evacuated. Part of the inner surface of the tube, or all of it, is coated with a photosensitive layer which is also a semiconductive substance. A fine wire in the centre of the tube is connected to the positive and the photosensitive layer to the negative terminal of a battery. Rays of light pass through the uncoated part of the tube, fall on the thin layer and eject electrons which fly to the positively charged collector wire.

But the current thus generated is very weak. A battery has to be connected in and then the tube merely *passes* the current instead of generating it. So the vacuum photocell acts much like a photoresistor.

A valve photocell is different: it needs no battery because it generates current. With a phototube like that a photoelectric device is, as a rule, simpler and cheaper.

Besides, the photo-emf in valve phototubes is much stronger than in vacuum cells, a fact which simplifies the design of automatic circuits. Sulphurous silver phototubes are a hundred times more sensitive than their vacuum counterparts. The advantage of photoresistors in this respect is especially striking: they are thousands of times more sensitive than vacuum photocells. Finally, semiconductor instruments are tiny hard plates, sturdy and reliable, while vacuum instruments are frail tubes.

In Kiev photoresistors and valve photocells are investigated under the guidance of B. E. Lashkarev, one of the most prominent specialists in the field, member of the Academy of Sciences of the Ukraine.

Designing these instruments are also scientists of Leningrad, Moscow and other cities. A great variety of such instruments already exists and ever new applications spring up.

Except for silicon photocells used as electric generators, nearly all semiconductor photocells have a too low efficiency factor—about one per cent—and are used only as elements of automation.

TIRELESS CONTROLLER

Automatic photoresistor devices have been used for several years in printing presses. One is designed to ensure admission of one sheet at a time. It passes a sufficiently strong current if it is hit by direct light or light which has passed through one sheet. If two sheets happen to get in at once there is not enough light, the current falls and the machine stops automatically.

Another takes care that the machine does not run without paper. A sheet of paper on the drum covers the photoresistor and "allows" printing. Otherwise a direct ray of light hits the photoresistor and printing is "forbidden".

The automatic safety device, installed on a huge press punch for which a thick sheet of metal is no more than a piece of paper, reacts in just the opposite way. The press can operate while light hits the photocell. If the operator reaches his hand under the press he shuts out the light and the machine stops instantly.

Recently photoresistors began working in the stacks of thermoelectric power stations. A metal cylinder with a lamp and photoresistor at each end is placed in the stack. The thicker the smoke, the weaker the light hitting the sensitive plate, the lower the current in the circuit and the smaller the deviation of the galvanometer needle.

Apart from controlling the supply of fuel to the furnace (avoiding excessive fuel expenditure and contamination of the atmosphere) this simple device opens the road to overall automation of boiler rooms.

In the same way photocells determine the composition of air in mines; the purer the air the more transparent it is,

the more light passes through. They also help to control processes at chemical plants and estimate blood composition at medical laboratories by gauging liquid transparency.

Certain photoresistors and photocells are sensitive to infrared radiation. Like bolometers they can be used for detecting heated objects and for photographing heavenly bodies in astrophysical research.

The instruments can also guard banks, museums or military installations. Invisible infrared beams guard all approaches to the building to be protected. Infrared rays can be obtained by screening an ordinary torch light with a piece of uviol glass. An unwelcome guest unsuspectingly crosses one of the beams and thereby announces: "I have come."

Some photoresistors react to X-rays. Simple and reliable instruments can therefore be built for dosing radiation in X-ray treatment. At iron and steel works photoresistors control the thickness of a rolled sheet: the thinner the sheet, the better the passage of X-rays.

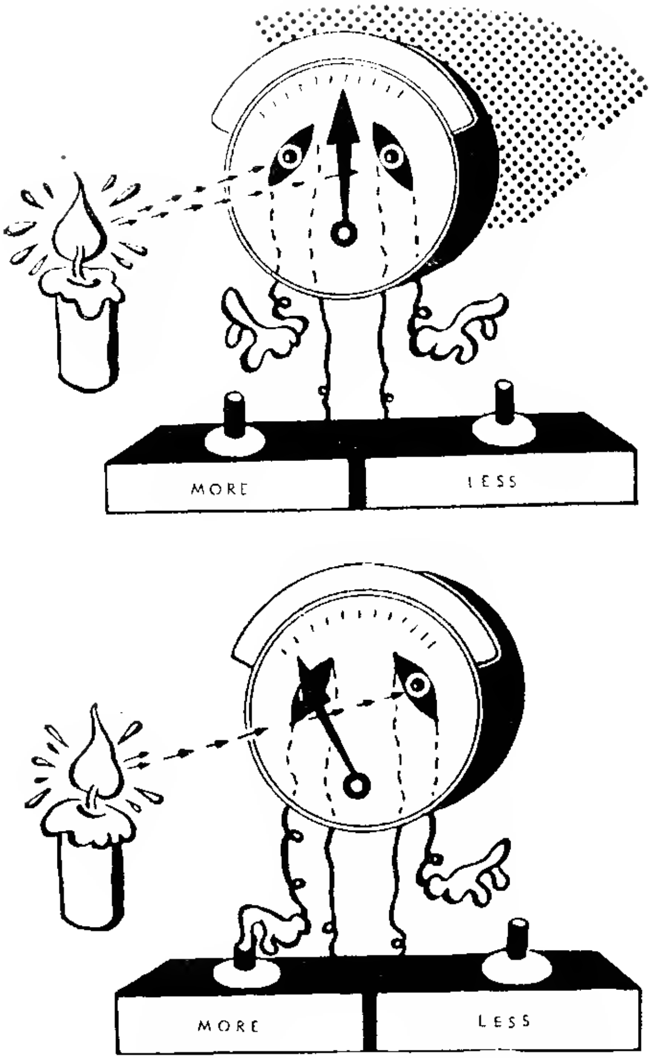
Finally, certain semiconductors change their resistance due to radioactive radiation. Sulphurous cadmium is a case in point. It can make a reliable nuclear particle counter or radioactive radiation gauge.

AUTOMATIC "HANDS"

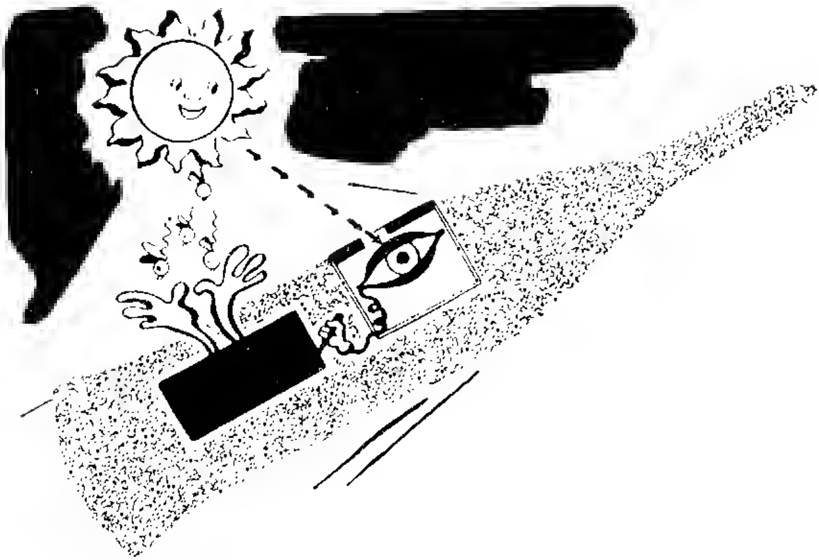
How can a photoelement stop a powerful press or a thermistor control the heating of an incubator?

Neither a thermistor nor a photoresistor nor a photocell is a self-contained automatic device. They are merely the organs of senses aided by an electromagnetic relay switch. If a photoresistor is the "eye" of the automatic device, the relay is its "hand".

There are many different types of relays. The simplest consists of an iron rod with several turns of insulated



The human eye symbolises a photoresistor. The tiny light-sensitive plates under the pointer automatically control pressure, temperature and weight



"Take in ultraviolet rays" is the photoresistor's command to a special device

wiring around it. The result is the conventional iron core electromagnet. At the end of the rod is an armature, an iron plate balancing on a spring. When there is a current in the winding, the core is magnetised and attracts the armature. If there is no current the armature is idle. A thermistor, or photoresistor or photocell in the same circuit changes the current and the armature makes and breaks the "actuating circuit" as it touches another, fixed contact (of this circuit). The two circuits, with auxiliary mechanisms, constitute an automatic device.

Let us see how this device works in a poultry-farm incubator. When it gets colder in the incubator the thermistor resistance increases, the current falls, the relay core demagnetises and the spring pulls off the armature. The contacts close and the heating system is switched on.

When the temperature in the incubator gets too high the procedure is reversed; the core magnetises and attracts the armature, and the heating system switches off.

In combination with the photocell or photoresistor the relay is known as a photorelay.

When a vacuum phototube is connected to a relay, it yields a very weak signal which cannot close the main circuit. To increase the power of the signal, an electronic amplifier is inserted into the circuit. Even then the photorelay can only switch on an electric lamp or sound a bell. If an electric motor has to be started, the photorelay must close another, more powerful electromagnetic relay starter.

The scheme is rather complicated, as we see. Here the advantage of semiconductor instruments comes into play. Many of them can yield a powerful signal which need not be amplified.

EACH HAS STRONG POINTS

Still, semiconductor instruments cannot beat vacuum photocells on all points. They have weaknesses—dependence on temperature, for example. Ironically enough, this dependence on which the operation of thermistors is based often proves to be an obstacle, and a rather serious one, in photoresistors and photocells.

Suppose a photorelay is installed in a beacon to switch the signal light on in the evening and off at dawn. In cold weather the photorelay will switch it on when there is still enough light because the conductivity of the photoresistor will fall, not so much from lack of light as from cold. Conversely in warm weather the beacon signal will not be switched on at all, since at high temperatures the conductivity of the photorelay will be sufficiently large to keep the electromagnet armature in place. Clearly, this device would be useless.

We shall come across many cases of entirely different tasks set for different semiconductor devices. What is useful in some is harmful in others. Researchers and designers often have to bring out one property in a semiconductor, magnifying it as much as possible, and keeping down all others.

The struggle against the temperature dependence of photoresistors has already been won. Photoresistors reacting comparatively weakly to the fluctuations of temperature have been made of sulphurous cadmium.

Semiconductor instruments have other shortcomings, the chief of them being slow response. They cannot be used when very quick action is required. Even photoresistors of sulphurous lead, the best in this respect, are fairly "slow".

Photodiodes, valve photocells in the circuit of another source of current, are almost free from this shortcoming. The current from the battery scarcely passes through a reverse biassed instrument in darkness, while the forward biassed current sharply increases with the increase of the intensity of light.

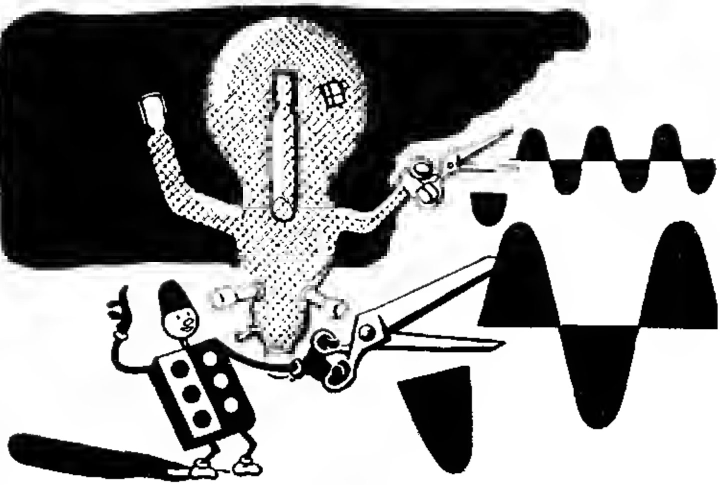
The external tension intensifying the internal field of the barrier layer gives impetus to the minority current carriers, "continuing a sunray" in the photodiode. Therefore, they move much more rapidly than in the usual photocell. The germanium photodiode responds to a light signal within one hundred-thousandth of a second, the quickest response of all semiconductor photocells.

Another instrument, a germanium phototriode, has appeared following the photodiode. This is a hybrid of a photocell and a crystal amplifier. It has three layers with two electron-hole transitions between them.

Light hits the middle layer and produces electron and hole pairs in it. In the usual two-layer photocell (and a photodiode) these charges, as we remember, run to the opposite electrodes and produce a photo-emf. Added to them in this case are the charges injected in large quan-

tities by the third layer, as in the amplifier. As a result the phototriode is several scores of times more sensitive with the same quickness of response.

Thus, new possibilities arise for photocells in automation. With every year the number of varieties increases and the range of application expands. Like photoresistors, thermistors and thermopairs, they are to become the pillars of technical progress.



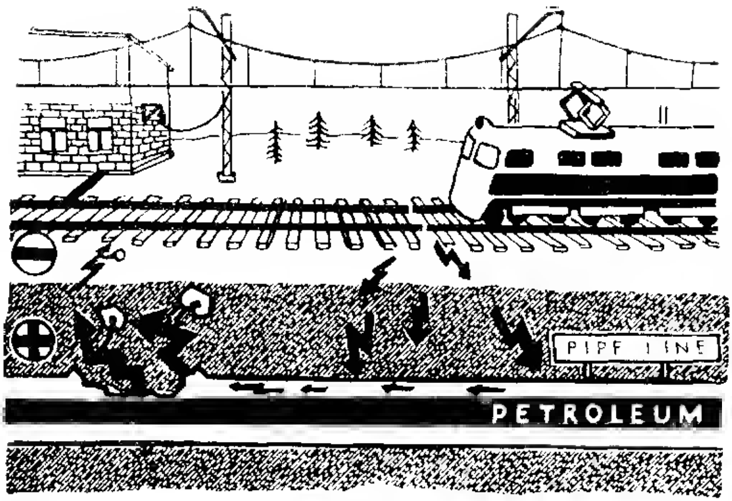
POWERFUL LILLIPUTIAN

"SENTRIES" BY THE CHIMNEY STACK

The pile of moist soil grew as the hole became deeper. There was a pungent smell of petrol. Smoking was strictly forbidden. A petrol pipeline was gradually exposed and several punctures were seen in its walls.

A team of repairmen had been called by a petrol pipeline walker. The team detected several scores of other damages. Many tons of precious fuel were lost. This was why the pressure in the pipeline had decreased so rapidly. Nor were the damages which ran into hundreds of thousands of rubles confined to the leakage of petrol and repair costs. What was still worse the pumping had ceased for a time and the works, deliverers in the "Second Baku" and consumers in Siberia, were at a standstill.

The trouble had been caused by stray currents. The pipeline runs not far from the electrified Ufa-Chelyabinsk

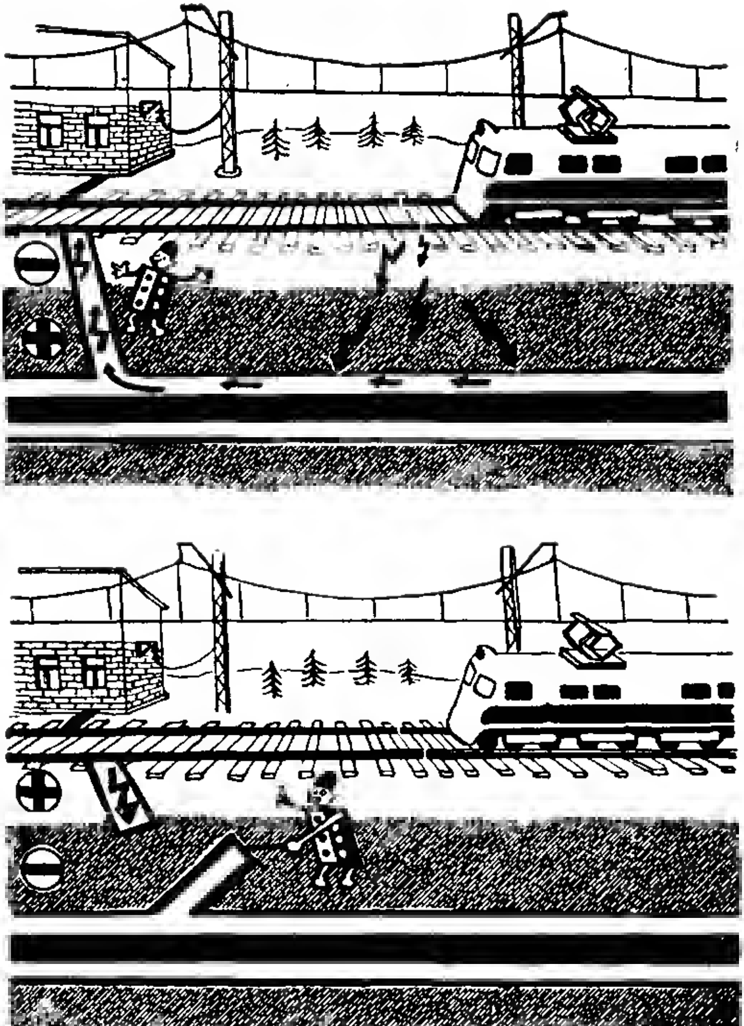


railway. Some portion of the current in electrified rails always escapes to the ground. If there is a pipe nearby the current runs through it and returns to the rails near a substation. The pipe is damaged at the point where the current leaves it because between the moist earth, acting as an electrolyte, and the pipe there occurs an electric chemical reaction which corrodes metal.

For protection pipes are coated with bitumen and thick paper. Sometimes two or even three layers are used. But when a pipeline is laid the coating often gets scratched, torn or displaced and the vagrant currents attack these spots.

The current is not dangerous while it runs through the pipe itself. The thing is not to let it escape to the ground. It might seem that the solution is simple enough. A cable should be laid to connect the pipe and the rails near the substation. The current will run across this metal bridge leaving the pipe without damaging it.

Actually, it is not so simple: the duty conditions of a substation are not always the same and the current is



Left: a stray current destroys the metal pipe. *Top:* the cable connecting the pipe and the rail protects the pipe. *Bottom:* should the current change its direction, the semiconductor rectifier blocks it and saves the pipe

liable to change its direction at any moment. Then the current will rush through the cable to the pipe and leak out at some other spot. In other words, the "bridge" must have a valve which would pass the current in one direction but block its path should it run in the opposite direction.

This valve is called a current rectifier. Quite recently a mercury valve was the most common rectifier. Unfortunately, this complex and heavy device is not suitable for field conditions.

Only rectifiers made of semiconductors are suitable for protecting pipelines against current eddies. Selenium rectifiers were once used for this purpose. Throughout the length of an oil, gas or petrol line a chain of "sentries" guarded the pipe against the sallies of hostile eddies and opened the circuit at the least provocation.

Selenium rectifiers, however, could not cope with strong currents. This is why the breakdown described above happened. A group headed by P. G. Doroshenko of the All-Union Research Institute for Laying Trunk Pipelines designed a new installation with powerful germanium rectifiers.

If you happen to travel by electric train close by a pipeline and see a smallish aluminium box attached to a post or resting on four supports, this will most likely be the improved protective device which has eliminated pipe corrosion and breakdowns.

Even when pipelines lie far from electrified, or indeed any other railway, they still are likely to be attacked by currents, though, true, these are not so strong. Where do these currents come from?

A pipe plus the adjacent soil make a galvanic battery. The processes at work between patches of exposed metal and the moist earth produce weak currents. This is why protective devices are also built for these pipelines.

The energy required for this purpose can come from a chemical battery, a fan-driven generator or a thermoelectric generator using natural gas which we mentioned in the chapter "Harnessing the Sun". It goes without saying that a semiconductive rectifier is an essential part of this protective device.

VALVE OR STOPPER?

The rectifier installed, say, at the substation of an electrified railway has much more to do than the pipeline sentries: it has to switch the current on and off, either passing it or barring its path to the contact line.

Alternating current is represented by a sine curve vacillating above and below a straight line. This means that the current constantly changes its direction and magnitude. The rectifier cuts the wavy line into two, as it were, passing the current from one direction only. Special devices smooth down the resulting pulsating current and convert it into uniform direct current.

In both nature and industry there are valves of all kinds for liquids and gases. Valves control blood circulation. Water or oil pumps, internal combustion engines and many other machines wouldn't run without proper valves.

But no valve, either in man's heart, or in a pump or an engine can compare with an electric valve as far as quickness is concerned. We shall describe only low-frequency valves for high energies. Known as power rectifiers these are used in electric smelting, welding, storage-battery charging and wherever direct current is needed. Semiconductor rectifiers are more and more often used for these purposes for they are small, simple in design and durable.

They first appeared 30 years ago. The primary material was copper. Since the properties of semiconductors are affected by impurities the copper must be very pure indeed.

Plates of copper, thoroughly cleaned and washed, are charged in a furnace. At temperatures above 1,000° C the

metal oxidises—combines with air oxygen—and a semiconductor layer, cuprous monoxide, appears on the surface of the plate.

This layer is not homogeneous: its internal part contains impurities of nonoxidised copper and other metals. We know that metals give up electrons readily and so this part of the monoxide becomes n-conductive.

Then the plates are transferred to a second furnace with a somewhat lower temperature (600° C) where the cuprous monoxide absorbs additional oxygen which captures electrons and produces holes. Thus the principal layer of the monoxide has p-conductivity. We have here the same "bread-and-butter" as in a photocell: the hole monoxide being the "bread" and the electron monoxide the "butter", with the rectifying transition layer between them.

Then another layer of metal is deposited over the cuprous monoxide, and the "sandwich" is wedged between two metal electrodes. This rectifier is known as cuprum-oxide or a cuprox rectifier.

Today the construction of a cuprox rectifier seems to be quite simple and the principle of operation perfectly clear. But not so long ago it was the centre of discussion.

It was believed that the barrier layer arose between the semiconductor and the electron metal. Experiments showed that these two produced a potential which increased the resistance in one direction and decreased it in the other. The difference, however, was always rather small: rarely was the factor equal to 2 or 3; usually it was even smaller. Yet the cuprox rectifier passed in one direction a current a thousand times as strong as that it passed in the opposite direction.

Another fact pointed to the need for further investigation. Suppose electrodes of different metals are pressed to both sides of the rectifier semiconductor? It was believed that a barrier layer originated on the border between the semiconductor and one of these metals but there was no

such layer at the other border; this depended on the properties of the metal and the semiconductor. But the second electrode in a cuprox rectifier was sometimes made of copper and then the same metal was pressed to the semiconductor on both sides. Logically there should have appeared two barrier layers; one should bar the current in one direction and the other in the opposite direction. The net result would not be a valve, but simply a stopper.

Nothing of the kind was actually observed, however. There was only one barrier layer in either case.

Then it was suggested that the barrier layer is not formed by the semiconductor-metal pair, but by two semiconductors of different types—electron and hole semiconductors. Researchers succeeded in confirming this experimentally; they discovered, between the hole copper oxide and the copper base, a fine layer of an electron semiconductor which had not been noticed before. It is the contact of this layer with the rest of the cuprox oxide that gives rise to a barrier layer something like one ten-thousandth of a millimetre thick.

These experimental facts are basic to the hole-electron transition theory which has been worked out by many Soviet and foreign scientists.

IN THE HEART OF THE ELECTRIC LOCOMOTIVE

Selenium rectifiers followed their cuprox predecessors. Both selenium and cuprox rectifiers are manufactured as small disks, flat washers, or square and rectangular plates. These elements are strung into long plastic-cased cylinders or ribbed piles very much like round or rectangular steam-heating radiators.

Cuprox rectifiers are widely used in various direct-current instruments, in railway automatic interlocking systems and so on, and selenium rectifiers in storage battery chargers, direct current film projectors, radio stations, electrolytic baths and in electric welding.

For all their advantages, selenium and cuprox rectifiers have serious shortcomings: they cannot stand high voltage in the barrier layer direction and their efficiency factor is low.

Germanium rectifiers, with a higher voltage limit and efficiency factor, naturally began gaining ground. Thus, they began to be used for the protection of pipelines, as we have mentioned above.

Nor are germanium rectifiers more complicated in design. The encased germanium rectifier is a thin germanium plate one or two square inches in area, with a bit of indium welded to it. This plate rectifies currents of hundreds and thousands of amperes and the efficiency factor is higher than that of any other rectifiers: 98 to 99 per cent.

The entire rectifier, also known as a power diode, is the size of a fairly small saucepan (including its casing and cooling system) but it can replace a motor generator housed in a large building. The motor generator is a current transformer consisting of two machines. Using an alternating current, one of them, an electric motor, rotates the other, a direct current generator. In many cases germanium rectifiers also oust mercury and selenium piles.

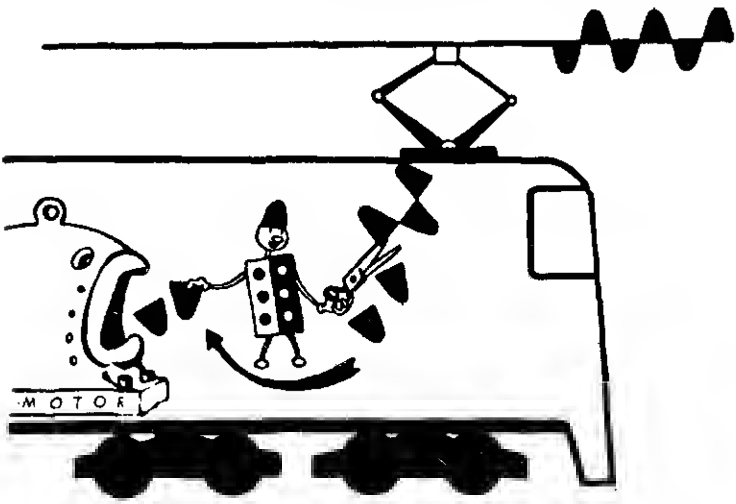
This makes us revise not only the possibilities of rectifiers, but also the entire problem of utilisation of direct current.

Until recently all electric locomotives collected direct current from overhead wires. It is very tempting, however, to switch electrified railways to alternating current. This dispenses with railway rectifying substations, yields an immense saving (since a direct current contact line requires only half of the copper) and increases the haulage capacity because more powerful locomotives can he used.

This means rectifiers will have to he installed directly on locomotives. Now, what sort of rectifiers? Motor generators are too bulky and mercury arc rectifiers too frail and cumbersome. Still, they *are* used in electric locomotives, in H-60 locomotive for example, manufactured by the Novo-

cherkassk Electric Locomotive Works. Suburban trains of this type have also been built.

Mercury arc rectifiers will not, however, stay in electric locomotives for long. They will be ousted by semiconductor rectifiers—but not of the germanium type.



By passing an alternating current only in one direction, the rectifier slices it in half, so to speak

Germanium has one peculiarity which limits the use of germanium diodes: it cannot stand heating above 70 or 75 degrees. The impurity effect weakens in the electron and hole semiconductors of the rectifier at such temperatures and its proper conduction, due to electrons and holes arising in great numbers in thermoatomic collisions, begins to predominate. As a result, the rectifier defeats its own end and passes current equally well in both directions. Powerful germanium diodes are water-cooled. Yet even this does not always mend the situation.

Silicon behaves much better. Its forbidden gap is wider and its electrons cannot easily reach the conduction band.

As a result, the number of proper current carriers in silicon is smaller than in germanium for the same temperature. Therefore, the effect of impurities in silicon is more perceptible and better refinement is required. This, of course, is an obstacle. From it stems the essential advantage of silicon—its high thermal "stamina". Powerful conduction arises in it at higher temperatures than in germanium.

Silicon amplifiers are capable of operating at temperatures up to 200°C. Besides, they have a higher electric voltage limit and higher power for the same size. This is why it is precisely silicon rectifiers that have come into their own on railways. Silicon rectifiers are to be installed in the new H-62 electric locomotive developed at the Novocherkassk Works. They are a trifle larger than so many match boxes. A score of such elements can do the work of a mercury discharge lamp the size of a man. They have another advantage: mercury arc rectifiers must not be heated above 35° C to 45° C, and so have to be furnished with a rather complicated cooling system, while silicon elements required nothing but an ordinary fan.

Suburban trains with silicon rectifiers have also been built in the U.S.S.R. They have shown a fine performance and are superior to similar locomotives made abroad.

Thus a.c. railway electrification has become a reality. The Soviet Union leads the world in the mileage of electrified railways. The new system has already been used on several large and heavy-haulage sections. A. c. contact lines extend further with every year and indeed with every month.

THE MAGIC PEA

VICISSITUDES OF FATE

Author Lev Sheinin recently recalled a visit he paid thirty-five years ago to an engineer who built radio sets as a hobby. "Come over to my house and you'll see a miracle," the engineer had promised.

"And so I went to see the miracle," Sheinin said. "Sprawling on the carpet the engineer's parents and the engineer himself clung to earpieces with an air of conspirators. He pointed to a black clumsy object intimating that this was the miracle which I had been invited to see. Then he pressed a pair of earpieces to my ears and over the din and crackle I felt rather than heard two bars of a Strauss waltz. My heart missed a beat and I looked at the engineer's grandmother who at that very moment, asked her grandson: 'Are you sure, dear, there is no witchcraft in it?' "

A few years after this episode crystal sets were on sale but strange as it may sound to the young people of today the radio was not so much a source of pleasure as of irritation.

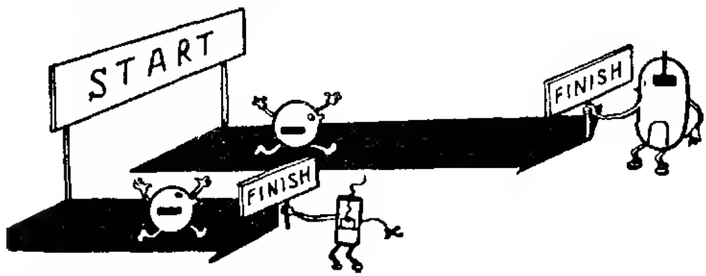
Its principal part was a detector, a semiconductor crystal with a metal spring. To tune in, the listener had to make the spring end touch different points of the crystal until he found the "sensitive point". This search took up much time. Nor was it always a success: the radio would continue to wheeze and crackle.

The detector is also a rectifier—not of usual industrial current, however, but of high-frequency current. It was invented in 1900 by Alexander Popov, the inventor of radio. The invention was a semiconductor device because radio tubes came later.

Crystals of galenite, zincite, pyrite and carborundum were used in the detector radio sets of the 1920s and early 1930s. At that time the rectifying transition layer was thought to originate at the semiconductor-metal border. The detector was designed according to this concept: a metal wire touched a crystal. Today it is clear that the "points" on the surface of the crystal were areas with a different type of conduction which originated by accident, with the resulting electron-hole transition.

The detector left the scene, forever it seemed, even before its secret had been revealed. A more reliable electron tube was introduced instead. Imagine a glass tube from which the air has been evacuated and with two electrodes in it—the cathode (a filament heated by current and emitting electrons) and the anode, a plate opposite it. Connected to the positive pole of a battery the anode attracts flying electrons, and a current runs through the tube. Connected to the minus pole, the anode repulses electrons and there is no current. Connected to an alternating current source, the tube only passes current in one direction. Everything is simple and reliable, in contrast to the detector. This two-electrode tube is known as a diode.

A large industry sprang up to manufacture radio valves. In due time, however, it became clear that radio valves also have many shortcomings. They are fragile, short-lived, too large and not efficient. But the gravest of their shortcomings came to the surface during the Second World War, when centimetre radio wavelengths, shorter than those used before, came into play.



Surely the sprinter on the shorter track is to win. The electrons in a crystal detector have the same advantage over those in a vacuum tube

The shorter the wave the higher the alternating current frequency. In city mains current flows fifty times a second in one direction and fifty times in the opposite direction; that is, it makes fifty complete cycles. The unit measuring frequency equals one cycle per second. So the mains current frequency is 50 cycles per second. Short-wave frequencies run into millions and ultrashort wave frequencies into thousands of millions of cycles. Electrical valves must open and close millions or thousands of millions of times per second.

It was found that a radio valve fails when frequencies are too high. Electrons cannot fly from the cathode to the anode as rapidly as they should at superhigh frequencies. In the conventional valves the flight equals a thousand-millionth of the second. Yet this is not enough for centimetre waves.

The investigation of silicon and germanium crystal detectors was resumed. The electrodes in them are situated

much closer to each other and the flight time must be shorter. The supposition proved to be correct. Besides, semiconductor detectors had been studied by that time and the rectifier contacts fixed at one point could be designed in advance—there was no need to look for a sensitive point. Nor did the new crystal rectifiers look like the detectors of the 1920s. Mounted on a special base, they could be replaced just like an electron valve.

True, valves have also changed a great deal since the crystal dctectors received a new lease of life. The conventional large valves are often replaced by miniature valves. Tiny valves with a cathode-anode span only several microns long have been designed, and more complex cathodes are now surrounded by a special grid, accelerating the flight of electrons. The frequency characteristics of electron valves have thus been improved a great deal.

It is this race for frequency in radio-engineering that stimulated the investigation of semiconductors, and their numerous advantages over valves soon became obvious. The incandescent cathode of an electron valve wears out in time and ceases to emit electrons. The valve lasts only a few thousand hours. Crystal detectors can last from 20 to 50 times as long. Semiconductor instruments are more sensitive than valves, and their efficiency factor is many times as high. Besides, they have no filament to be heated and so no energy is spent on incandescence and they are always ready for action. Finally, they are small and shockproof.

WAVE-AIRCRAFT AND WAVE-PASSENGER

Today there are detectors of different types. Some of them are like power diodes: a plate of electron germanium is welded to a piece of indium. The resulting electron-hole transition has a rather large area and therefore these instruments are known as junction diodes.

There are also point-contact detectors with the sharp end of a metal spring welded to a germanium crystal.

The result is a rectifying transition layer as small as a point.

The smaller the contact area the smaller the charge the instrument can accumulate—and the lower its electric capacity and the quicker it is recharged as the direction of current changes. Point diodes can therefore be used for rectifying much higher frequencies than junction types.

To say that the detector simply rectifies current is not quite accurate. It is not just a rectifier like a power diode: its performance is more complex. To get an idea of it, let us trace the course of a radio wave from the radio studio to the radio receiver.

As a singer performs the microphone generates low-frequency, electrical oscillations. These oscillations cannot be transmitted by radio. They should first "board" high-frequency oscillations excited by a special valve oscillator at the radio station. The high-frequency is a "plane" in which the useful signal will travel.

To begin with, the low-frequency signal is amplified by a valve. This corresponds to a motorcar taking the passenger to the plane. Next comes the "embarking", that is, modulation: high-frequency oscillations are given the "shape" of the low-frequency curve. Then another valve amplifies the high-frequency oscillations which are radiated by an aerial as radio waves: the "plane" takes off.

The "plane" has arrived when the radio wave has reached the receiver. It has brought an infinitesimal share of the energy radiated by the transmitter aerial. It is as difficult for the receiver to "hear" the signal as for the human eye to see an electric torch at a distance of hundreds of kilometres. That is why the high-frequency oscillations that have reached the receiving aerial get first of all into the amplifying valve. The "plane", which has run out of fuel, is thus tugged in, so to speak.

Now the signal should be "disembarked", taken off the high frequency, separated from it. That's a job for a detector. Apart from rectifying the high-frequency alternating

current, it isolates the useful low-frequency signal which is amplified by another valve: the passenger is carried from the plane to the airport building. Finally, the amplified signal is sent to the loudspeaker to be converted into sound.

In other words, a detector is only one valve among many in a radio receiver. Besides, only the simplest receivers without superheterodynes are designed that way. Modern radio sets are much more complex.

The diodes in receivers, transmitters and other radio systems account for merely 10 to 30 per cent of the total. The other valves being all sorts of amplifiers, high-frequency oscillators, etc., are more complex than diodes. They have at least three electrodes, because between the cathode and anode there is another electrically charged grid. When charged negatively, the grid obstructs the motion of electrons to the anode, and when positively, accelerates it. Small changes in the grid potential lead to strong oscillations in the anode circuit. Therefore weak electric signals sent to the grid are amplified in the valve.

The remarkable features of crystal detectors naturally suggested this idea: why cannot amplifiers be made of semiconductors? The question recalls experiments made by gifted Soviet researcher O. V. Losev nearly 40 years ago, in the "tender youth" of semiconductor device operation.

MAJOR MILESTONES

In 1921 and 1922 Oleg Losev, a research associate of the Nizhni Novgorod radio laboratory, discovered that crystal diodes could not only serve as detectors but also as amplifiers and even high-frequency oscillators. He designed a radio set without a single valve; quite an advance by the standards of that time.

Already in those years Soviet radio engineering scored impressive successes: the world's largest radio station was built and a record for distance of communication estab-

lished. The Nizhni Novgorod radio laboratory was a major radio research centre at that time. In this laboratory the world's first powerful water cooled electron valve was designed and the experiments in the transmission of speech by radio were staged. It could well be expected that it was in this laboratory that a new method in using crystal instruments would be found.

News of Losev's discovery quickly spread to other countries and roused intense interest among radio specialists but research was soon discontinued because of the development of the electrovacuum industry which began producing radio valves on a mass scale.

In 1948 the American scientists J. Bardeen and W. Brattain added another contact to a germanium point-contact diode as they studied its properties. They obtained two electric circuits: each biassed by a battery. Unexpectedly, the scientists noticed that whenever there were weak current oscillations in one circuit there were stronger oscillations in the other. Now this is just what happens in a triode, a three-electrode valve—an amplification.

In 1948 scientists manufactured the first crystal triodes which they called transistors, and then radio sets without electron valves. One of their compatriots described their invention in this way: in 1948 a delayed atom bomb the size of a pea appeared in radio engineering.

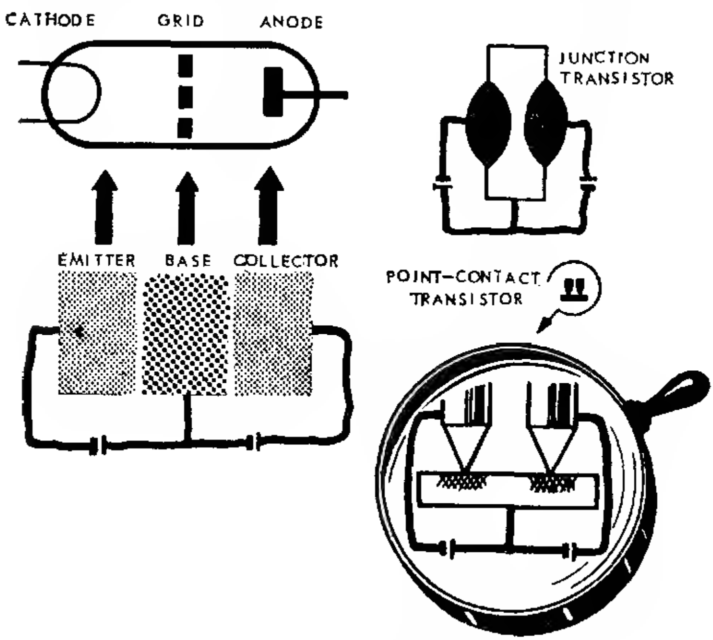
The significance of the invention became more apparent with each year. Improved types of transistors appeared in many countries.

We discussed the construction of the semiconductor amplifier in the chapter "One in a Thousand Million". Recall that it has two electron-hole transitions. In our graph the left transition is biassed in the forward direction. This is an "electron syringe". It "injects" portions of minority current carriers into the middle layer and these carriers move on unimpeded, through the right-hand transition.

This amplifier can well be compared with a triode valve. The left-hand layer of the transistor, known as the emitter,

corresponds to the cathode of a valve; the right-hand layer, known as the collector, to the anode, and the middle layer, called the base, to the grid.

Just as in case of diodes, there are point-contact and junction transistors. The junction triode is essentially a



The transistor is similar to a triode valve

strip of n-germanium with dots of indium melted onto both sides to produce p-germanium layers. This device can increase the power of a transmitted signal thousands of times.

A point-contact amplifier is constructed somewhat differently. Two fine wires under which two p-semiconductor "points" are formed are welded to a plate of n-germanium. This kind of transistor works like the junction type, but its power is lower.

Yet a point-contact triode, like a point-contact diode, has a low electrical capacity due to a small area of contact. Therefore it can work at higher frequencies than a junction triode.

Of major importance is the thickness of the middle layer: the thinner it is, the shorter the route of charged particles. In a point-contact triode the distance between the sharp ends is 0.05 mm while the layer of electron germanium between the hole points is even thinner. In certain junction triodes the thickness of the base is reduced by a special pickling process to 5 or 6 microns! Not every microscope can discern such parts.

We have described the simplest semiconductor amplifiers and their connections. Actually there is already a great variety of triodes and their applications are many and varied.

The amplifier and the transistor mark two major milestones in the history of semiconductors: the former paved the way for their practical application while the latter made them vital elements of radio engineering.

RADIOWAVE INSTEAD OF A BATTERY

Radio telephones are now commonplace, widely used in militia, fire engines, emergency cars and taxis.

A pocket radio telephone no larger than a cigarette box and weighing a little over a pound is no novelty either. The owner can be called up from any telephone, including street booth telephones, since a special installation will connect all ultrashort wave telephone users with the usual telephone network.

Such telephones will in time become common and there will be no telephone lines, thousands of tons of nonferrous metals will be saved and an army of line supervisors dispensed with. Semiconductors make this feasible.

A transmitter a little larger than the usual telephone once seemed impossible. Radio operators all over the world

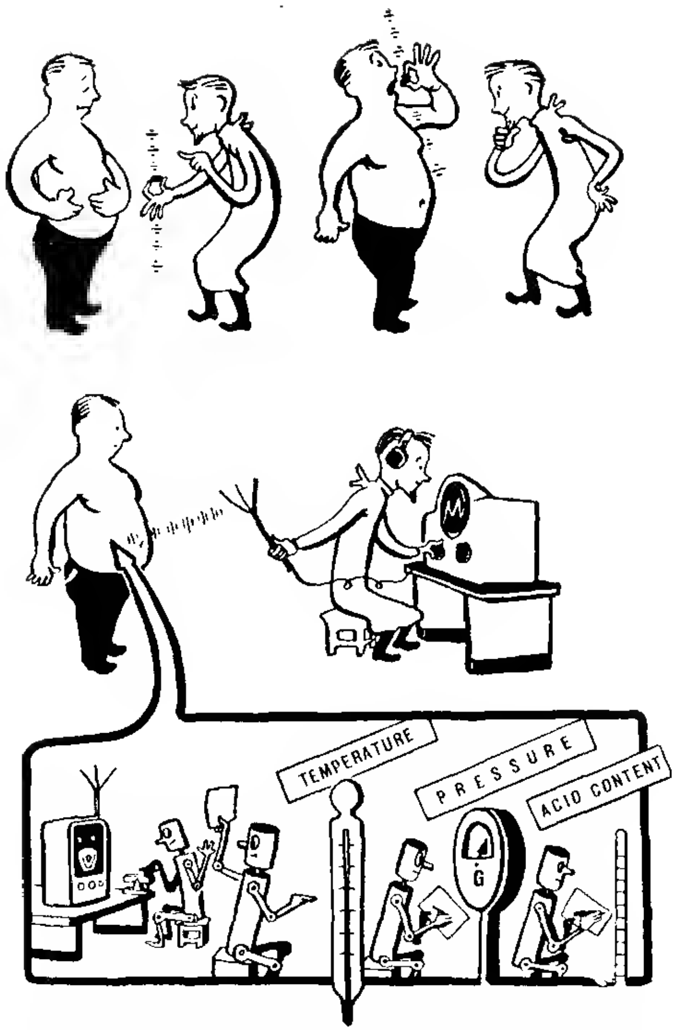
receive signals from such transmitters installed aboard Soviet Earth satellites.

A transmitter and receiver mounted inside the telephone receiver is a reality, too. A transeiver of this kind, Nedra-1, with a range of 30 km is manufactured in the U.S.S.R. for geologists.

In Japan radio sets are encased in ordinary watches. They are tuned permanently for the time service wave length. The time is announced as soon as a button is pressed.

But the record for miniatureness seems to have belonged until recently to a radio transmitter in a pill, which also contains tiny instruments determining the temperature, pressure of the walls, and acidity in the stomach and intestines. For several hours the tiny laboratory sends radio reports on the health of the patient who has swallowed it. This pill was designed a few years ago by Manfred Ardenne, a prominent scientist of the German Democratic Republic. Now such pills are used in many countries, including the U.S.S.R. Quite recently we talked with its designers, a team of Leningrad engineers. The pill is even smaller than its G.D.R. counterpart. It is 20 mm long and 8 mm thick. The patient wears a special belt with an antenna to receive the radio waves from the pill. Then the signal runs through a wire to a receiver on the physician's desk. The transducer in the pill, measuring acidity, temperature or pressure, changes the frequency of the generator's oscillations and so the physician learns the results of the analysis. Obviously this method of probing gastric juice, for example, is much more pleasant than the conventional method.

Nor can such pills be used for medical examination alone. Doctors often have to keep a constant watch on the patient when he lies bedridden or walks about. How can this be done? How can a grave attack of illness which might prove fatal be prevented? Semiconductors come to their help.



The tiny pill contains an honest-to-goodness laboratory showing temperature, pressure, acidity, and, last but not least, a radio transmitter and a battery, all of which are made of semiconductors

A device the size of a small coin is attached to the lobe of the ear; on one side of the lobe is a tiny lamp and on the other, a photoresistor. The latter reacts to the pulsation of blood and even the change of its composition. The medical ear-clip reports on the patient's pulse, haemoglobin content and temperature. Whenever alarming signs appear, an automatic device warns the physician on duty.

So far such devices have been used only at in-patient clinics. But in time the automatic nurse will accompany the patient *after* his discharge from the clinic. Only the power of the miniature radio station will have to be increased.

Electronics has made it possible to examine not only the patient but—and this perhaps will have more far-reaching consequences—the healthy organism in its natural environment. For the first time science can obtain reliable information on all kinds of processes in the activity of the worker at the bench, the sportsman during a contest, in fact, of any person in his natural environment. Soviet inventor L. P. Shuvatov and his team invented a set of microdevices which are taped to any part of a human body without constraining movement. Each device weighs from a gram and a half to several grams and the whole system weighs from 40 to 300 grams, including a radio transmitter in a helmet.

The new branch of radio engineering, biotelemetry (measurement of physiological data by radio) had undergone a very serious test during the flights of Soviet cosmonauts. Of course the signals were transmitted not from their helmets, but the system was essentially the same. Nowadays we take the miracles of science in our stride. We are no longer surprised that Gagarin and Titov were under continuous medical supervision throughout their flights. The world marvelled at the levelheadedness of Yuri Gagarin who had the normal pulse before the start. His pulse was taken with the help of modern biotelemetric aids.

What was unthinkable a short time ago becomes a

daily occurrence. When a patient's cardiac rhythm breaks down he is saved by an electrostimulator, a device which stimulates his cardiac activity by electric pulses of the wanted frequency. Quite recently the device was a cumbersome affair weighing about 30 kilograms and the patient was attached to it by wires. Now it is a box, no larger than a pocket watch and weighing only several scores of gram, which is fixed to the patient's body. No wiring is necessary. The patient only has to drop in at the clinic five years later for recharging. Once again semiconductors do the job.

We said that until recently the record for miniatureness belonged to a radio transmitter pill. Now there are devices so small that the radio transmitter pill seems a giant. There is, for example, a radio station in a human tooth. Fantastic isn't it? A transmitter is inserted in the tooth to study it in detail. The most vital part of the hearing aid reduced to the size of a pea is sewn under the patient's skin near the middle ear.

Each electronic device of this kind has a power source: a midget battery installed in a pill, electrostimulator or a "dental radio station". These examples graphically show that semiconductor radio instruments are not only miniature, but they also consume very little energy and require very small batteries.

Sometimes, chemical batteries can be dispensed with altogether. In the chapter "Harnessing the Sun" we mentioned a portable radio set with silicon photocells. The size of a smallish book, such a set is powered by light energy, and in the darkness by a tiny storage battery charged by the same photocells.

Nor is light indispensable. A radio set powered by radio waves has been designed. The set in fact consists of two sets: one tunes into some powerful radio station and transforms the waves into electricity for feeding both sets, while the other picks the required wavelength.

Finally there is a radio set powered by the energy of

the human voice. True, it is not very powerful and has only one triode.

The saving is especially striking when crystal instruments replace electron valves. In TV sets, for example. The TV set Sputnik designed in the Soviet Union has not a single vacuum valve, except for the cathode-ray tube. The set requires no more than one-twentieth of the power consumed by a valve TV set.

Sputnik won the Grand Prix at the World Fair in Brussels. An improved version, Sputnik-2, was on show at the Soviet Exhibition in New York. The designers believe they will soon design a semiconductor TV set for mass production. Battery-powered this portable TV could even be used in trains or motorcars.

Millions of radio and TV sets produced annually in the U.S.S.R. consume nearly 1,000 million kilowatt hours a year and only a fraction of this energy is spent usefully: the efficiency factor of the conventional receivers and TV sets is very small. Crystal diodes and triodes, on the other hand, cut the consumption of electric energy by at least 95 per cent.

It is even more important that the substitution of semiconductors for valves will increase the reliability and service life of radio equipment. Valves are fragile and capricious. There is a good dozen of them in every modern first-class receiver and nearly two dozens in a TV set. The valves in these sets need to be replaced comparatively rarely. But in radio relay lines, radars or TV transmitters, which employ many more valves, replacements are quite frequent despite a close supervision of their duty conditions.

There are scores of thousands of valves in electronic computers. This product of human genius, alas, occupies several rooms and sometimes even several floors and is naturally very expensive. And yet the machine pays off its cost within twenty-four hours of work. The explanation is that the machine calculates very rapidly and gives accurate estimates.

The reliable operation of these machines is all the more important. In recent years more and more often semiconductors replace valves. The world's first electromodelling installation without a single valve was designed a few years ago at the U.S.S.R. Research Institute of Computing Machinery. This machine, the size of a suitcase, successfully replaces a much larger installation and consumes no more energy than a 100-watt lamp.

Today there are even smaller computers in the U.S.S.R. and other countries. British scientists, for example, have developed a semiconductor computer the size of a match box.

Apart from being a computor and a translator, the electronic machine can also be a remarkable operator of a machine-tool, a plane or a rocket. Thus semiconductors become an element of higher automation.

The semiconductor has raised the role of radioelectronics. A curiosity not so long ago, the semiconductor has become a mass-scale product intended to extend the introduction of radio engineering in industries and research as well as improve man's living standard.

A FACTORY-JEWELLER

Large tables encased in metal and glass stretch in long, regular rows. On each table there is a micrometer. Next to it there are glass jars with ground stoppers.

Germanium crystals reach the tables only after preliminary treatment. First an ingot of germanium is sawed into small plates which are polished, pickled, boiled in a solution of hydrogen peroxide and sodium hydrate and finally rinsed in distilled water. A young girl sorting out the crystals piles the tiny grey petals on the micrometer table and with her pincers puts them under the measuring head. The needle makes perceptable jumps, showing a deviation of one micron.

A micron, a thousandth of a millimetre! The lightest stroke of a sharply pointed pencil is scores of hundreds

of times as wide. But here it is a micron that counts. Crystals of the same size go into one jar; even an extra micron sends them into another—to be used in another type of instruments.

Seated at similar tables other young girls in an adjacent room assemble an electron-hole transition: here goes a nickel wire as thin as a hair, there a dot of indium (one millimetre in diameter), a crystal of germanium, another dot of indium, one-half the size, and another piece of nickel wire. This work calls for a jeweller's skill and experience.

The junction thus assembled is placed in a graphite adapter, then into an oven for baking, after which it is tested, boiled and rinsed again, varnished and encased.

But the main trouble begins when the finished triodes are tested. Identical transistors are a rare thing! They are divided into several types and deviations are inevitable in each type. The production is too delicate. For example, the base in many triodes is a hundredth or even a thousandth of a millimetre thick and the slightest deviation from the required magnitude sharply changes the properties of the instrument. Recently, even the distilled water for rinsing transistors was found to contain ions capable of producing extraneous harmful charges in the instruments. A new operation was introduced—deionisation of the distilled water by ion exchange of resins or ionites.

The dissimilarity of transistors of the same category is a usual feature known as the divergence of parameters. Nor is this the only defect of transistors.

We know that germanium diodes and triodes do not work when heated above 70° C to 75° C. Silicon is less finicky and works at 170° C to 200° C. But even this temperature limit is not always sufficient. Sometimes the defect can he neutralised; in the chapter "Electronic 'Wind' Transfers Heat" we described thermostats for radio sets. Enclosed in small (also semiconductor) refrigerators, triodes and diodes are capable of resisting higher tem-

peratures. This does not always solve the problem, however.

Probably the worst defect of transistors is their frequency barrier. Whereas semiconductor detectors have fine-frequency properties right from the start, transistors show a much worse performance: their frequency limit is still considerably lower than that of electronic amplifiers. Low-frequency valves in radio and TV sets are not always replaced by semiconductors, while this has long been the case with low-frequency valves.

More complex instruments are designed to raise the frequency limit of transistors. A fourth electrode is added, for example, and so we have a tetrode instead of a triode.

New semiconductor radio sets have been designed recently. They are called spacistor and thyristor. The former is a combination of plane diode and point triode and the latter is a germanium column with a slender waist encircled by a ring of indium. The ring acts as the control grid in a three-electrode radio valve while the upper and lower part of the column, with different quantities of impurities, act as the anode and cathode respectively.

The development of these instruments offers the hope of raising the frequency limit up to the level of the best valves.

Finally, triodes have another weak point: set noise. Everyone has heard a light purr in the loudspeaker of a radio set. This purr originates because the current in electron valves constantly changes even without any external influences. The cause is the chaotic thermal oscillations of the cathode particles. In crystal instruments such oscillations are much more intense because the current carriers have to move through a solid. These oscillations interfere with the amplification of very weak signals which are drowned in the transistor's own noise.

Intense research is being conducted in this direction. An instrument called a versitron has been designed; it is a semiconductor triode immersed in liquid helium. At

temperatures close to absolute zero (—273° C) the electric conductivity of the versitron decreases sharply and the set noise disappears. The atoms scarcely move at all, collide rarely and weakly, do not create free holes and electrons, and the only charge carriers prove to be those which have come from outside and brought the useful signal.

In such conditions the triode is able to receive and amplify extremely weak signals, such as from outer space. These signals are detected by radio telescopes. The versitron, however, requires a cumbersome and expensive cooling system which called for some essentially new departure in radio engineering.

It is obvious that transistors have some disadvantages. But the very awareness of them suggested the right direction for the development of research.

MOON WITHOUT "VEIL"

Lunik-3 is the peak of the development of science, the highest achievement of human genius. This is what was written and said in all languages following the launching on October 4, 1959, of the Soviet automatic interplanetary station which circumnavigated the Moon along a complicated, predetermined orbit. Later followed fresh, still more amazing achievements, and new superlatives were found, but at that time that was indeed the highest peak. The world was amazed by the boldness of the project and accuracy of its execution. The smallest error in the initial speed could have ruined the whole undertaking. This time even greater accuracy was required than for Lunik-2 which placed the pennant of the U.S.S.R. on the Moon. It was also contemplated that after the circumvention the interplanetary station would return to the Earth. That was especially vital since during the circumvention the station was to photograph the Moon's hidden side. Having completed the loop of the trajectory, the station transmitted

by television the picture of the Moon's reverse side back to the Earth. That victory for Soviet science had eclipsed the previous records. The first successful experiment of space television seemed more amazing than either the accuracy of launching or ground control of spaceships.

In October 1959 the automatic station, orientated first by the Sun and then by the Moon, trained its lenses and for forty minutes photographed the never-before-seen side of the Moon. The film was processed automatically, in a state of weightlessness. That in itself was a miracle of modern automation but something even more amazing followed.

A television transmitter started up as soon as the film processing was over. A needle-thin ray illuminated the film point by point, line by line and frame by frame. Each 35-millimetre film shot was resolved into a good thousand lines. No terrestrial TV set has such image resolution.

And then the distance! For terrestrial TV sets the limit is less than 100 kilometres while the transmission distance for Lunik-3 was about 470,000 kilometres.

"I was amazed by the accuracy and high quality of the photographs, and consequently the equipment used for photographing and transmitting the images. Even for the high standards of Soviet science this is a truly remarkable achievement," wrote Professor Sir Bernard Lovell, Director of Jodrell Bank Observatory, a leading British astronomer.

The first experiment in space television was a brilliant success and it would have been impossible without semiconductors.

MEASURING OUTER SPACE

In outer space the principal measuring standard is the astronomical unit equal to the mean radius of the Earth's orbit. Until recently it was assumed to equal 149,500,000 kilometres. Though this unit had been determined by many methods, their accuracy was not too high and the pos-

sible error ran into hundreds of thousands of kilometres.

What did it mean in practice?

A Mars-bound rocket might have passed scores of thousands of kilometres wide of the mark. Not because the trajectory had been miscalculated, but solely because the calculation was based on an incorrect space unit of length.

Such an inaccuracy was once tolerable, but in the age of space travels it became a hindrance. Soviet science obtained a more accurate astronomical unit length—149, 457,000 kilometres. The possible error is only 5,000 kilometres or one-twentieth of the previous error.

The astronomical unit was usually determined in this way: the distance to a planet was measured and the calculation made by the well-known laws of celestial mechanics. The old methods of measurement of interplanetary distances are too rough, however, and here is where radar comes in: a radio pulse is sent to the planet and its echo is detected on the Earth.

Extremely powerful transmitters are necessary to span the interplanetary vastness. Even so, the "back" signals are so weak that only highly sensitive receivers can detect them. The first experiments in radio-ranging the Moon and Venus were not very successful. The signal sent was weak and the measurements unreliable. The tape-recorded echo of Venus was so weak, indeed, that it took a year to decipher it! Recently, however, Soviet scientists succeeded in the reliable radio location of Venus. The power of the radio beam had to be increased five million times as compared with that used in beaming the Moon.

A more accurate astronomical unit was not the only result of this remarkable experiment. Until then man had not known the velocity of the revolution of Venus because a dense and impenetrable atmosphere shrouds the planet. Due to the experiment it was established beyond doubt that Venus makes one revolution in approximately ten terrestrial days and nights.

Such are the remarkable discoveries made with the aid of modern radio engineering, including semiconductor engineering.

TUNNEL DIODES

Several years ago the study and improvement of crystal amplifiers became one of the key problems of engineering. Nearly every day papers on semiconductors appeared in scientific magazines of different countries. A good half of these dealt with transistors and other semiconductor amplifiers.

The number of types snow-balled. Not all of them, of course, were able to stand the test of time, but those which gained a footing in the field were numerous enough.

We shall describe only one of them, but one that is likely to make radio engineering history.

It is known as the tunnel diode. The return to the diode is not at all surprising. The fact is that this is an extraordinary kind of diode and it has a lot to do with amplifiers.

In the chapter "One in a Thousand Million" we wrote about the ladder that can lower the potential energy barrier which springs up when two different types of semiconductors, n-type and p-type, are put together. This barrier explains the peculiarity of the barrier layer.

An outer electric field can either raise the barrier and then no current will cross it, or lower it (if the battery terminals are reversed) and thus pass a flow of current. This is how the semiconductor diode works as a rectifier.

The situation may, however, be different. A rather strong flow of current is observed though the barrier is high enough and no current should flow. This once nonplussed physicists. Now it is known (and we have discussed it) that the elementary particles have wave properties and hence the apparent eccentricity of their behaviour.

Let us imagine the energy barrier as a high rampart. Electrons (or holes) cannot scale the barrier because they

lack energy. It appears, however, that they may get through the barrier by cutting a kind of tunnel in it (hence the term tunnel diode).

This can be compared to light penetrating a normally opaque thin film. The barrier layer in the tunnel diode must also be very thin. For that purpose more impurities are introduced in both n- and p-semiconductors, increasing the number of current carriers a thousand or even a million times as against the conventional diodes and transistors.

A device of this kind cannot be used as a rectifier because the reverse current in it may be quite strong. But this is not the main specific feature of the tunnel diodes. When the outer potential is forward biassed and smoothly increases from zero upward, the current in the diode sweeps up and attains a large value, whereas in the conventional diode there is practically no flow of current if the voltage is low. Then the current drops to increase gradually as in any diode.

This initial jump is due precisely to the tunnel effect. In this region the diode is extremely sensitive to the slightest change of voltage. Hence its success as amplifier, generator or transformer.

Let us recall the main defects of transistors: frequency limit, a high noise background, the danger of overheating. The tunnel diode is far better on these scores. Besides it is very small and consumes a fraction of the energy required by the most economic semiconductor device. And last but not least, the tunnel diode is much more sensitive than the transistor and its amplification ratio is much higher.

Tunnel diodes first appeared three years ago and they are exceptionally valuable in computers. Computers employing tunnel diodes are highly reliable, efficient and small in size. For example, an electronic brain less than the size of man's head, capable of 500,000,000 operations per minute, is being developed at Cambridge University, Britain.

MICROSCOPIC RADIO SET

When we discussed miniature radio sets we concentrated on detectors and amplifiers. There are other parts in the set however, all kinds of coils, capacitors and resistors. Quite recently soldering was only one method for connecting them. If we replace all radio valves by semiconductor detectors and amplifiers and leave all other parts as they are, the set will not be much smaller.

When miniature diodes and transistors came on the scene, radio designers began to reduce the size of other parts and simplify connections. Thus, the printed circuit was evolved. A circuit is printed on an insulator plate with a special paint containing metal conductive power. The printed circuit replaces the most complicated tangle of wires. All we have to do is to connect tiny devices to the plate and we have a radio set.

The soldering shop has become a printing shop. Incidentally, circuits can be printed in different ways: an insulating base can be plated with a foil on which acid is applied, or the wanted pattern can be obtained galvanically, by depositing metal out of its solution.

Next step towards simplifying the technology and reducing the size of the set was taken when the circuit and the device began to be printed. Graphite rectangles or strips of nichrome were used as resistors, metal layers on both sides of an insulation plate as capacitors, etc.

Then a new idea sprang up: a plate with a ready-made circuit could be cut and the pieces used as standard units of radio equipment, just as prefabricated panels, are used in housing construction.

Then thin ceramic plates with all necessary parts replaced insulation plates. These ceramics are collected into packages filled in with a special resin. The devices thus produced are very small (scores of parts are contained in one cubic centimetre), sturdy and reliable. Today they serve as foundation stones for radio engineering.

But inventive genius is never idle. Perhaps not separate parts, but entire circuits could be painted on ceramic plates. Thus microcircuits were born and miniature devices were replaced by microminiature, and printed circuits by filmed ones.

The thickness of a film element is from several tenths to several thousandths that of a human hair and its area a fraction of a square millimetre. And the most surprising thing is that triodes, and not only resistors, capacitors, etc., have that size and shape. The emitter-base, collector, p-n transitions are all fitted into that unbelievably thin film.

In the next chapter we shall describe the manufacturing of these devices. Here we shall merely mention the fact that with the appearance of filmed radio parts, semiconductor micro-metallurgy replaces semiconductor metallurgy.

Progress did not stop there, however. Why should a ceramic base plate take up extra space? Why not assemble everything right on a semiconductor piece? Then the entire volume will be effective and a set (or some other apparatus) will have no extra weight.

This circuit (known as a hard circuit) is based on a tiny plate of silicon or germanium. It is powdered in a high vacuum through several standard stencils and deposited on its surface are metal layers to serve as connections, and impurity layers to serve as detectors, triodes and resistors. The plate is heated and the impurities penetrate the semiconductor. Then an oxygen atmosphere is created in the furnace and an oxide layer, necessary for a capacitor, originates on the surface of the semiconductor, etc.

The circuit contains a thousand or even more parts in one cubic centimetre. Now a whole set may only be the size of a pea. A set the size of a millet seed is anticipated. And the main thing is that such circuits are hundreds of times more reliable than their predecessors.

It is difficult to differentiate parts in hard circuits. Thin layers of a crystal, molecular groups of a substance, act

as different parts. This is why the new stage in the development of radio engineering is called molecular electronics.

There is another method of manufacturing molecular electronic devices. A single crystal can be produced instead of depositing different layers over a semiconductive plate. True, only initial steps have been taken in this direction. But before long we shall not see any wire, or coil, or plate at a radio works, but only vessels and solutions, heaters and coolers. It will be something like a chemical plant. Whole stages of p-n transitions will be grown by changing the composition and temperature of solutions. Some transitions will act as detectors, others as amplifiers, still others as capacitors, or resistors, or power sources.

A tiny stratified crystal capable of receiving without any energy, except for light or radio waves themselves, is no longer a fantasy, but a problem awaiting a practical solution.

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HUNTING FOR NINES

ROBINSON CRUSOES OF OUR CENTURY

The number 99.9999999 designates the purity of germanium when it contains no more than 0.0000001 of dope, one ten-millionth of one per cent! One atom of dope for each thousand million atoms of germanium! The hunting for nines is now in full cry. Some ten or fifteen years ago it was established that a semiconductor can pass muster in radio engineering if it has from six to ten nines, the more the better.

Scientists were depressed by these figures. Before the Second World War the highest purity attained in nonferrous metallurgy did not go beyond three nines: 99.9. The fourth figure was with hard work brought to 8. And that was a very high laboratory hallmark.

How could fresh nines be obtained?

Obviously, the former refining technique was no good. And then suppose the wanted number of nines had been obtained. How could this be verified? There were no adequate methods of analysis. These had to be created.

Furthermore, the refining equipment and the chemicals used in the process had to have an unprecedented degree of purity. One insufficiently sterile section of the process could spoil the whole effort.

The material obtained had to be protected against moisture or dust. It was not enough to purify the air in the premises—the premises themselves should have smooth, washable walls, with a coat of paint capable of resisting erosion or pulverisation without any cornices or embellishments where dust could accumulate. Yet pure as the air might be, it was still dangerous to so pure materials and they had to be protected against it.

In other words, literally everything had to be created anew. At the most up-to-date research institutions and well-equipped laboratories the scientists were in no better position than Robinson Crusoe on his island: they had to start from scratch.

Incidentally, it is not only semiconductor engineering that is so strict with respect to the purity of materials. Atomic fuel and some reactor materials, for example, must be purified no less thoroughly. Aircraft engineering and many other branches also need superpure materials.

To solve this fantastically complicated problem representatives of many sciences—physicists, chemists and metallurgists—had to pool their efforts. As a result, the old and familiar materials appeared in an altogether new light. It became clear that science was not aware of the true properties of many metals. For example, titanium was regarded unsuitable for machining, but now it is manufactured into sheets and strips and intricately shaped parts are pressed out of it. Refined thoroughly, aluminium that we all know so well, becomes as soft as lead. Many semiconductors did not reveal their remarkable properties un-

til they had crossed the borderline designated by a certain number of nines.

Today semiconductors have come to the foreground in engineering, and this turning point would have been unthinkable without the contribution from the "hunters for nines".

A GRAIN OF GAIN IN A YEAR OF LABOUR

Germanium began to be produced commercially in the U.S.A. as soon as it became clear that after thorough refinement it can be used for detectors. The first attempt was made in 1942, but by 1946 merely half a ton of commercial germanium had been obtained!

In the U.S.S.R. this work began after the war but progressed much more rapidly. Our scientists were not travelling a beaten track since the Americans had not disclosed their secrets. It was rather because our scientists advanced on a broad front. At institutes and laboratories in Leningrad, Moscow and Kiev, they studied, experimented and groped for the new techniques of germanium refinement.

From the outset our scientists had to deal with two problems. One was refining germanium, and the other mining for it.

We have mentioned that Winkler discovered germanium in argyrodite fifteen years after its prediction by Mendeleyev. Later on other similar minerals (germanite and rhenium) were discovered in the Congo. All of them contain small percentage of germanium. But these minerals occur very rarely and their deposits are insignificant. No other ores have yet been found to contain germanium. It would be inaccurate, however, to say that germanium is a rare element.

The "rarity" of an element is a very conventional concept. Is lead a rare metal? Of course not. But vanadium, of which there is fifteen times as much, certainly is. The

fact is that there are lead ores which contain much of this metal, while vanadium occurs only as impurity in the ores of other metals.

There are rare elements whose extraction is especially difficult: only traces of them are found in certain minerals. These elements are known as trace elements. It is to this group that germanium belongs, though the terrestrial core contains seven times as much germanium as lead.

Surveying for germanium showed that its resources are very sparse and meagre. For example, zinc blender from which zinc is obtained, contains a large group of trace elements: indium, gallium, tallium and germanium—in insignificant quantities, of course.

If one-tenth of one per cent of indium is found in zinc blender, it is used for extracting indium, rather than zinc. This shows how much some trace elements are valued. Though there is even less germanium in zinc blender, germanium is obtained from zinc waste products.

In Britain, a few thousandths of one per cent of germanium were discovered in the ashes of Northumberland coal, and the British thought themselves lucky. Waste products of the coal industry: the resins and ammonia waters of coke works as well as the dust and soot of gas-generating instillations also became sources for obtaining germanium. All sorts of waste products, the "tailings", formerly dumped, often proved more valuable than the original products.

Hundreds of thousands of tons of raw materials must undergo many stages of processing for one ton of commercial germanium to be obtained. By conventional standards this metal is rather pure. It has no less than two nines: 99 per cent of germanium and only one per cent of impurities. And yet it is altogether unsuitable for semiconductor engineering; as a raw product it has no semiconductor properties at all.

And here is where the real trouble begins. Before infinitesimal impurities were finished out of minerals and

ores. Now undesirable impurities have to be taken out of germanium so that only those imparting adequate properties to it remain or could be added. And each new nine is harder to get than its predecessor.

Not all impurities in highly purified metals are equally harmful and dangerous. For example, niobium may contain any amount of tantalum; they are "next of kin" and do not spoil each other. Germanium and silicon "are related" to carbon and tin: their tetravalent atoms are firmly bound in the atoms of the semiconductor and produce neither electrons nor holes. Copper is the worst enemy of germanium: the slightest trace distorts its properties. So, the concept of nines is relative. When we say that impurities in germanium account for 0.0000001 per cent, only dangerous impurities are meant. The number of nines does not designate absolute purity of germanium, but only its purity with respect to these harmful contaminations.

Obtaining superpure metals is a recent development. It calls for powerful and advanced enterprises capable of processing millions of tons of raw materials, concentrating rare metal to an unprecedented degree, and refining it of all impurities. The process will not pay unless the extraction is an integrated process; that is, all valuable components extracted.

Only modern engineering in the most advanced countries is capable of this performance. The immense role that superpure rare metals play in widely different fields make the increase of their production imperative. This increase becomes an index of a country's economic development.

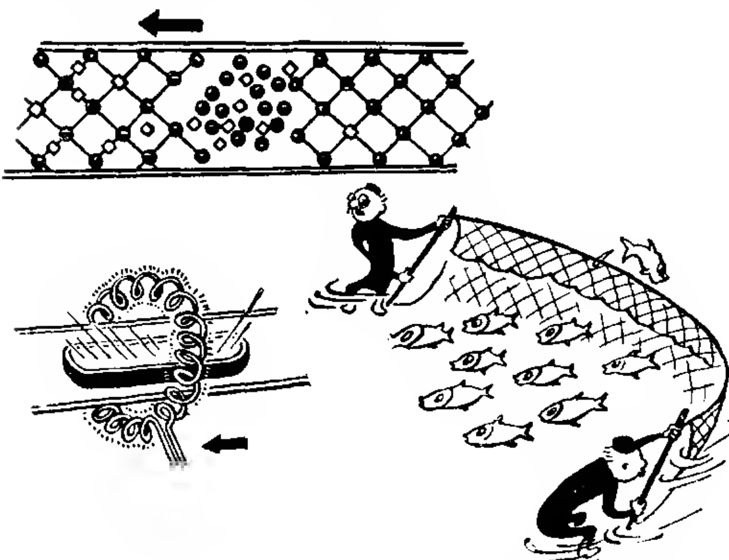
While only 16 elements were extracted in tsarist Russia, the nonferrous metallurgy of the U.S.S.R. puts out commercially over sixty elements. But now others are needed.

"NET" AND "FISH"

When fishermen net a lake not all the fish will be caught at once, of course: some will slip under the net, others leap over it or squeeze through the meshes.

A net of a kind has been invented for extracting impurities from germanium.

The "lake" is a quartz tube, with the air pumped out or replaced by an inert gas, argon. In the tube lies an ingot of germanium in a ladle of graphite.



The molten band moving along the germanium crystal and catching the "fish": impurity atoms

The "net", a ring electric furnace, encircles the tube. High-frequency current flowing through the furnace melts germanium without touching it. The furnace ring moves slowly along at a rate of several centimetres an hour.

The melted band moves through germanium at the same speed. The ingot behind the band hardens again but

becomes purer as most of the "fish", extraneous atoms, are carried along in the moving melted band.

Each time the process is repeated more impurities are driven towards the end of the silver-grey ingot. Sometimes, instead of passing one ring furnace along, the tube, several furnaces move one after another. Sometimes the furnace is immovable while the tube moves. But the principle remains the same: the impurities are "raked" thermally towards one end which is then cut off and scrapped. The bulk of the ingot can thus be reduced to a very low level of impurity: less than a millionth of one per cent.

Why do the impurities travel in the molten germanium and scarcely if, at all, pass into its solid part?

When germanium begins to harden, its atoms take up their places in the crystal lattice, each of them, as we know, getting connected with four neighbours. If impurity atoms occur among them, these unwelcome strangers find it much more difficult to get a footing in the lattice than in the chaotic mass of the molten germanium atoms. So most of them stay in the liquid fraction. Incidentally, freshwater ice originates at sea sometimes for the same reason.

So the "net" is not the furnace but the "crystallisation front", the crystal lattice in the making.

True, this is not always the case. An impurity may cling tenaciously to the crystal lattice in the making and a larger amount of it will then be found in the lattice than in the liquid fraction. Then it is the other end of the ingot that is the "dirtiest". Sometimes an impurity is in its element in both liquid and solid crystals, such as boron in silicon or arsenic in antimony. Fortunately, there are no such impurities in germanium. In general, the method described is quite suitable.

This method is known as band smelting. It would be more correct, however, to call it band recrystallisation. This method was designed especially for the refinement of semiconductors, and later began to be used for obtaining other superpure metals.

When the molten band moves, the ratio between the amount of an impurity, which gets into the lattice and that which remains in the molten germanium, is always constant. This constant is characteristic of each impurity and called its distribution coefficient.

This is an important feature of the process. It makes it possible to calculate in advance how many times the furnace should move along the ingot to obtain the wanted purity. The initial content of the impurity should be known, of course. The same feature makes it possible to determine the amount of the useful impurity, usually added to germanium at the end of band smelting.

We already know that impurities impart a hole or electron conductions to germanium depending on the elements of which the impurity consists. These dopes should be introduced in strictly definite infinitesimal quantities. To obtain electron germanium, for example, one-millionth (0.000001) of one per cent of antimony should be added. It goes without saying that the antimony is refined, and very thoroughly too, since it always contains copper. If antimony accounts for 0.0001 of one per cent of copper, the latter will 0.0000000001 of one per cent in germanium. But even such infinitesimal quantities of copper affect the properties of germanium.

But how are these infinitesimals measured? Any former method of analysis would be about as suitable as seeking an atom with a magnifying glass.

Chemical analysis is far too rough. Spectral analysis, the subtlest of all until recently, is also weak. Using it only six nines (four nines after the point) can be detected. Of course, these methods could be made more sensitive, but this involves all sorts of complications and repeated processing of the substance under study, to concentrate the impurity and thus make it traceable.

New physical methods, radio activation for instance, have appeared on the scene. The latter method essentially comes down to putting the sample under investigation into

an atomic reactor for neutron irradiation. Thus, radioactivity is excited in the impurity atoms and they become "tracers", reporting their presence, no matter how few they are. Their reports have only to be read with the help of a special counter detecting radiation.

The electric properties of germanium obtained may also be tested, for these largely depend on the amount of impurities. It is these indirect methods that are used most often to test the purity. The Hall effect, for example, can reveal a thousand-millionth of one per cent of an impurity.

BEHIND SEVEN LOCKS

After band smelting, the bar of germanium mostly consists of a few or many crystals. Just like ice, germanium expands in crystallisation. Cramped within the crucible, it cracks from within and forms two or more crystals. Other defects are likely to appear during this process.

A single crystal, or a monocrystal, has a more regular structure. It can only grow gradually, like an icicle from a roof. But it has to grow behind seven locks, so to say, in severe isolation protecting germanium against any external influence. We watched this process in a laboratory.

Having washed her hands carefully, an operator with large forceps (also washed in a special solution) picked an ingot of band-melted germanium from a jar fitted with a ground stopper. The ingot was of a greyish colour—something mid-way between silver and steel. She put it into a bowl of quartz and rinsed several times with hydrogen peroxide. The same solution with the ingot in it was covered with a quartz lid and put on a fire.

The solution was boiled for a long time and then replaced by twice distilled water which was used to rinse the ingot and then to boil it again.

With the forceps the ingot was then quickly transferred into a graphite crucible, a black round cup the size of a saltcellar, and the crucible was quickly placed on the

stand of an apparatus for growing crystals. A vertical quartz tube was lowered over the crucible and pressed tightly to the stand. We heard the "jug-jug" of a vacuum pump and soon our ingot was in almost a complete vacuum. But "almost" was not enough. Traces of air, especially oxygen, could penetrate into the lattice of germanium when the crystal was grown and spoil everything by changing the type of conduction or decreasing the electrical resistance. An artificial hydrogen atmosphere was therefore created around germanium from a special cylinder which supplied a constant stream of hydrogen to the apparatus.

But hydrogen, too, could be "dirty". Therefore it was forced through a coal trap which absorbed all impurities. The trap was immersed in liquid nitrogen since its performance is better at lower temperatures; and then it was encased in a vacuum flask wrapped in moist gauze to keep the nitrogen from evaporating too rapidly.

Finally the electric furnace encircling the crucible was switched on. The ingot subsided, turned into liquid, its pink lustre reflecting the red-hot coil. The temperature of the melt was about 1,000° C. Atoms of different substances interact especially actively at such temperatures. This is why it is so important to protect germanium.

The young girl technician turned a lever and a seed crystal was lowered into the crucible on a thin, long rod. It was a tiny crystal of germanium cut from a very pure monocrystal ingot. The seed crystal touched the melt and began to rise very slowly as the motor lifted the rod. At the same time the seed crystal revolved to give the ingot a more regular round shape and more uniform composition, for there are still some impurities in germanium!

Scarcely perceptible, yet steadily, the silvery crystal rose from the pink-tinted liquid. The crystal looked almost like its progenitor. Still, it was a monocrystal. Usually it is not altogether spherical, but has facets with very regu-

lar curvatures. By these facets a specialist can always tell a monocrystal from a polycrystal ingot of germanium of the same size and shape.

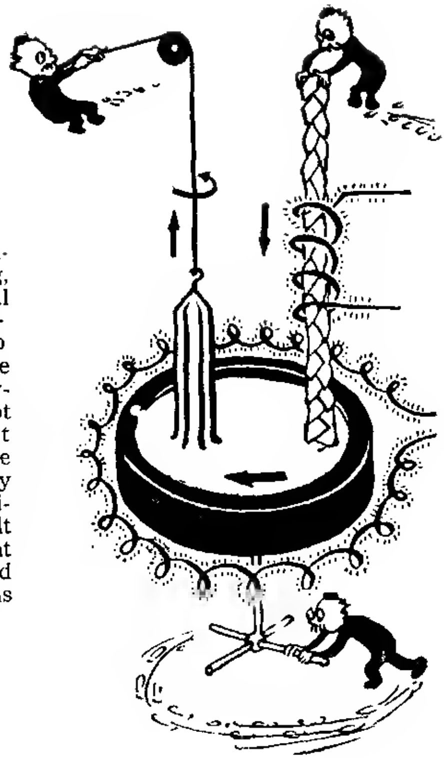
We have described the laboratory growing techniques. An industrial installation for producing large monocrystals is much more complex. It has a host of accessories for control, outside furnace cooling, etc. A glance at this installation will show that not only metallurgists, physicists and chemists, but also designers had to do a great deal before semiconductors in so high a state of purity could be obtained. The production and refinement of germanium in the U.S.S.R. should be credited to a large team of scientists headed by N. P. Sazhyn, Corresponding Member of the Academy of Sciences of the U.S.S.R.

In the previous chapter we described our visit to a radio factory where semiconductor amplifiers are made and learned the bitter meaning of the expression "straggling of parameters". This scourge complicates the use of transistors even in those cases when their frequency, temperature and other properties are satisfactory.

The causes of the "straggling" can be traced to the processes at work long before the transistors are produced and even before the ingots of germanium reach the radio factory. One of the principal causes lies in the ingots themselves and comes to the surface during the production of monocrystals.

The crystal-growing technique is a variety of band smelting, with the only difference that the entire ingot is first smelted and then it hardens by bands. So in this case, too, one end of the ingot is purer and the other is "dirtier". The lower end can be cut off and scrapped. But the remaining monocrystal is not uniform either. It has more impurities towards the lower end. Devices made of such ingots would have different properties.

Can this defect be eliminated? Something can be done about it. If the rate at which the crystal is pulled is accelerated, more impurities will be captured by the lattice.



Besides purifying germanium, the crystal drawing, which follows the usual band melting, imparts a regular, perfect structure to germanium. Shown in the sketch is the melt-feed drawing: a polycrystalline ingot of germanium, heated almost to the temperature of the melting point, is gradually lowered into it. The quantity and quality of the melt remain therefore constant throughout the process, and the drawn monocrystal is uniform as a result

Slowing-down, on the other hand, will decrease the amount of impurities.

So the purity of germanium can be controlled by the rate of growing. To obtain a more uniform ingot, a certain growing rate programme can be established in advance, the rate will change by schedule: the more impurities in the melt, the slower the rate. This growing rate programme is widely used at laboratories and enterprises.

The amount of impurities in the crystal increases with their increase in the molten germanium. Therefore a compromise method is applied; the growing process is divided

into several stages. The product becomes composite: the few centimetres on top are the purest, the next section has more impurities, etc. Each section therefore is uniform, but they differ from each other, and this is also undesirable.

A new growing technique has been worked out at the Institute of Metallurgy of the Academy of Sciences of the U.S.S.R. Germanium of the same composition as the growing crystal is gradually added to the melt. Two crystals move over the crucible: a polycrystal sinks as it melts, while a monocrystal, now almost uniform, is pulled up. In the installation designed for this purpose both melt and crucible rotate and so the added germanium mixes much better.

The new installation helps in another even more involved process.

If from time to time different impurities are thrown into the molten germanium, sections of different conduction, with electron-hole transitions between them, will appear in the drawn crystal. So far we have been discussing the production of transitions by alloying germanium. Now, it appears that molten germanium can be doped while the crystal is pulled and the distribution of the dope over the length of the crystal controlled.

The same can be brought about in a simpler way: two dopes, gallium and antimony, for example, are added right from the start. The distribution of antimony strongly changes with rate of pulling, while that of gallium remains constant. Molten germanium is so doped that more gallium will be captured when the rate of pulling is slow (and so a hole layer will result) and more antimony when the rate is more rapid (and so an electron layer will follow). By changing the rate of pulling, several electron-hole transitions will be produced in one monocrystal.

Using the conventional rate growing technique, however, it is simply impossible to make all transitions uniform,

since the dope concentration in the molten germanium changes. Now the quality of diodes and triodes entirely depends on the transition properties. Even the pulling rate programme cannot take into account all processes at work in the molten germanium as the crystal grows.

Only the new technique of feeding molten germanium into the new installation solves this problem. Since the composition of the melt remains constant in this installation all transitions are identical throughout.

But even pure germanium is not enough. A perfectly uniform monocrystal would be far from the ideal, since all sorts of disturbances, known as shifts, are inevitable in its lattice. Just like impurities, these affect the electric properties of germanium. How do the shifts originate and what can be done about them are problems which science has merely touched so far.

INACCESSIBLE CITADEL

The refinement of germanium is difficult enough. It calls for ingenuity, caution and patience.

Comparatively, the refinement of silicon is an inaccessible citadel high on a steep cliff. The difficulties that scientists encountered in this field proved to be far greater.

True, the raw materials are plentiful enough. A quarter of the earth's crust is silicon. Yet it never occurs in pure form, but always in combination with oxygen. To divide them and then refine silicon was the question.

Pure crystalline silicon melts at a temperature above 1,400° C, or nearly 500° C higher than germanium. At this heat no vessel can protect silicon against atoms of other substances which attack fiercely, seeking to combine with it. Molten silicon dissolves or "washes out" even quartz walls, thus bringing in oxygen and other impurities. These latter contain, as a rule, boron (the separation of which is especially difficult), iron, magnesium and aluminium in such quantities that they can easily be detected by spec-

tro-analysis. Yet silicon requires a greater degree of purity than germanium! To be on a par with germanium, or as specialists put it, to attain an equivalent refinement, silicon must contain a thousandth of the impurities that germanium is allowed to have.

The task looks hopeless. Perhaps it's not worth trying? Perhaps silicon should be given up for ever and replaced by, say, germanium? No, this would not be right, since we know that silicon in many cases is far superior.

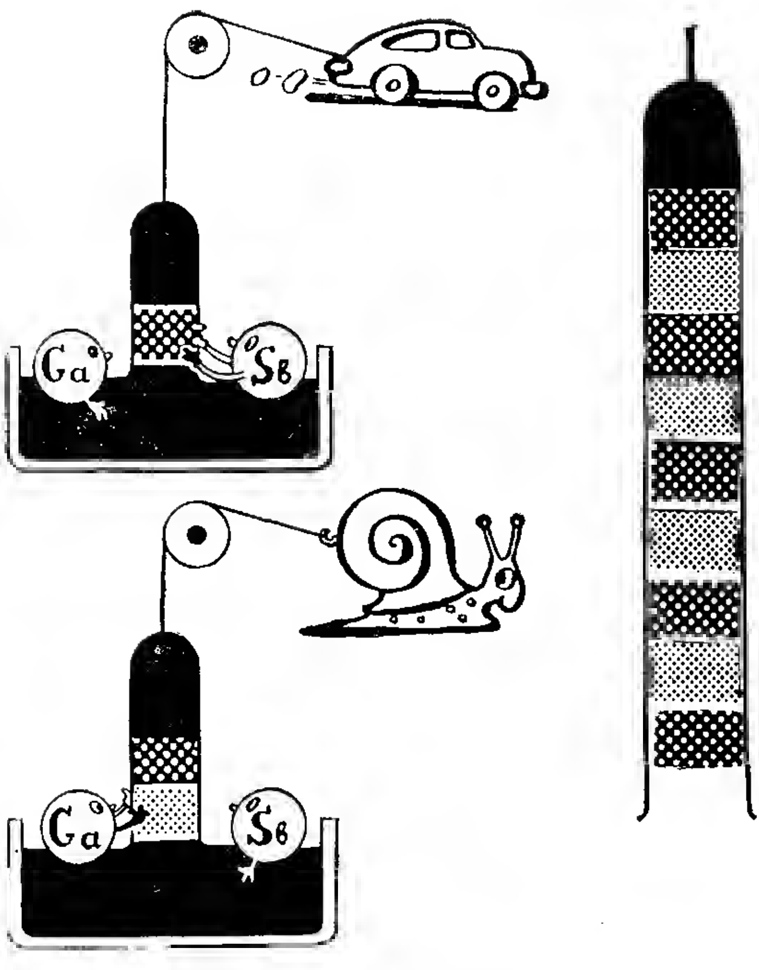
Let us recall that those nines, which now signify the purity of germanium, were inaccessible quite recently. Their number has doubled within a few years. Some ten or fifteen years ago no chemist on Earth could cope with what is now an industrial process. And the way out for silicon has been found too.

As far back as in the middle of the 19th century the Russian chemist Beketov proposed the following method of obtaining silicon: first he obtained a compound of silicon and silicon chloride (which is not difficult) and then ousted silicon by zinc. This process occurs at 1,000° C and therefore can be realised in a quartz tube.

If vapours of zinc and silicon chloride are mixed up in a quartz tube, silicon crystals will precipitate. Thin and long, tapering to one end, tinged with blue, they are like sewing machine needles and that is why they are called needle crystals.

This method is used even now, though it does not, in itself, ensure any particular purity of silicon. How can purity be achieved? First of all the primary substances, zinc and silicon chloride, should be purified carefully. But the main trouble begins when the needle crystals are obtained. They are pickled with purified acids to remove the particles of zinc which cling to the surface. After several hours of boiling in different acids the crystals are rinsed two or three times in distilled water.

The process is not yet over, however. Now these unprepossessing black jagged needles approach the



In drawing a crystal from a melt containing two impurities, different layers may be produced by changing the drawing rate. For example, the crystalline lattice of germanium absorbs more antimony (Sb) when the drawing is rapid and more gallium (Ga) when it is slow. The result is a stratified crystal. Now we have only to slice it, put each slice into a capsule with taps, and here we have detectors or transistors all complete

crucial stage of treatment. In sealed vessels they are transferred to the installation for manufacturing monocrystals.

SERVING AS ITS OWN CONTAINER

Beketov's is not the only method. But the monocrystal stage is inevitable in any case. To make a monocrystal, silicon should be first melted. But in what? The container should resist the heat, be as pure as silicon itself, and keep it free from contaminations at temperatures close to 1,500° C. No such container is known to exist as yet. Crystals of silicon are grown just as crystals of germanium, but crucibles of quartz, not graphite, are used. A poor material such as natural quartz is still the best. Possibly, ultrapure silicon for quartz containers will be obtained artificially some time.

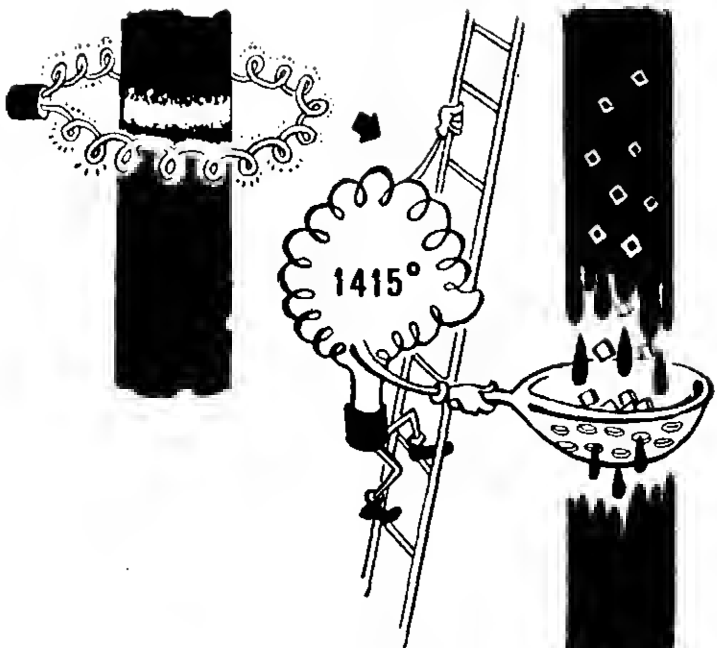
In the meantime scientists are trying to get rid of the crucible altogether. How can silicon be melted then? In mid-air? Well, nearly so.

A piece of silicon is fixed vertically inside a quartz tube in a vacuum or in a suitable gas. Moving along the tube is the ring electrical furnace which melts a belt of silicon about one centimetre high. The furnace slowly moves up or down and the melt band shifts along with it.

The molten band hangs in mid-air due to the force of surface tension. The ingot is used as its own container.

This noncrucible band melting is no easy job, of course. The slightest error is enough for the silicon to pour down and the sample be spoiled. But a skilful operator can produce a first-class crystal.

But this method is not very efficient. Besides, the process is possible only when ingots of silicon, and not just separate needle crystals, are available. The noncrucible band melting improves the structure of the crystal and can purify it additionally by "chasing" the impurities from the crucible to one end. Though this method does not



Melting without a container. Sounds odd, doesn't it? Yet super-pure silicon for radio devices can be obtained by such non-crucible band melting

dispense with the crucible and pulling technique altogether, it is a step forward. Today the researchers are working on the automation of this process, to make it independent of the operator's art.

Doping silicon is a field unto itself. At a temperature of about 1,500° C dopes sublimate from the melt almost instantaneously. Whenever a uniform crystal of a definite conduction has to be grown, the environment of the dope vapours is created over the molten silicon.

As you can see all the difficulties encountered are formidable.

It is not surprising that highly pure silicon is very expensive and is not available in sufficient quantities. But intense research is paving the way into engineering for this semiconductor.

As for the finest techniques for obtaining it, they do not seem too impressive after the miracles of micrometallurgy, the film technology we described in the chapter "The Magic Pea".

The finest film pattern is produced in high vacuum. The chief tool is an electronic ray. A powerful electron beam hits, say, a plate of germanium and evaporates it. The semiconductor atoms precipitate on a cold backing nearby covered by a special stencil so that germanium can be deposited in a definite pattern. The ray is shifted onto other plates: of dielectric whenever a capacitor is needed, or of metal if a resistor or some other part is to be produced. Other stencils are put over these backings.

The process can be fully automated and then the ray will operate according to a preset programme and the installation will manufacture sets of perfectly identical prints.

NEW MEMBERS OF THE FAMILY

Germanium and silicon are the principal radio semiconductors. But others, even better in many respects, have already appeared.

Since the elements have been studied sufficiently well, different compounds are tested. The combinations of the elements of the third and fifth groups of the Periodic Table yielded the most encouraging results. These are the elements used as dopes for germanium and silicon, to impart a certain type of conduction. It appears that the combination of two different substances like that produces something similar to germanium or silicon.

Do you remember the canteen which served us as a model of germanium and silicon, the elements of the

fourth group? Each of their atoms has four valence electrons and the tables had four chairs respectively. The addition of an element of the fifth group was symbolised by a table with five chairs and element of the third group by a table with three chairs.

Now imagine that all tables in the canteen are arranged in pairs and one table in each pair has three chairs, while the other has five. Three plus five is the same as two times four. In other words, the elements of the third and fifth groups combined are similar to those of the fourth.

Soviet scientists tested pairs of aluminium and antimony, indium and antimony, gallium and antimony, gallium and arsenic, and others. The first pair has shown an especially good performance. This is a typical semiconductor with a broad forbidden gap (much broader than in germanium or silicon). Therefore the new semiconductor can easily resist heating above 300° C. In other words, the thermal barrier of this new semiconductor is almost twice as high as that of silicon and almost four times as high as that of germanium. The immense importance it might have in radio equipment cannot be overestimated.

Besides, this new arrival is likely to surpass silicon as the material for solar battery photocells.

What then is the snag? Refining again. This material is not yet sufficiently pure: it has only five or six nines. The aim is eight nines, and the "hunters for nines" are trying to rope in the missing nines. The problem is a hard nut to crack. There being two components, the process will be more complex and by far more expensive than refining germanium or silicon and so the simplest possible methods of refining must be found.

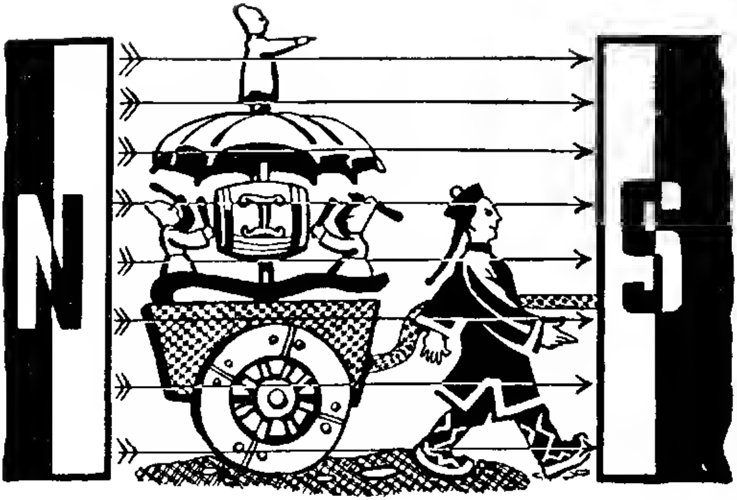
Other pair combinations are also promising. For example, the compound of silicon and carbon, of the fourth group, is silicon carbide which possesses valuable semiconductor properties at high temperatures.

Meanwhile combinations of three or even four compo-

nents are being investigated. The family of germanium and silicon is growing.

A new, apparently unexpected possibility has arisen in recent years: making semiconductors with definite frequencies right out of atoms and molecules instead of wasting time and energy on the purification of natural semiconductors. Semiconductor chemistry has arrived to supplement semiconductor metallurgy.

There are already many synthetic semiconductors, including polymers. They combine the electric properties of semiconductors with elasticity, durability and other qualities, and this opens up entirely new possibilities. It is quite probable that these newcomers will dominate the scene in the future.



THREE VICTORIES

DOWN WITH THE CONTACTS!

The telephone buzzed and the engineer on duty at the pumping station picked up the receiver.

"How many pumps have you on," he heard the dispatcher's voice.

"Two."

"Well, that explains the drop in the pressure. Don't you remember that the expenditure of water increases at this time and other pumps should be on?"

"Straightaway. How many should I turn on?"

"Turn on another two."

Such is the old control routine of the water supply system and indeed the entire complex municipal facilities of many towns. Nor is there any remote control in the power systems of most industrial enterprises—at their

compressor and pump installations and transformer substations.

Perhaps this is regarded as something second-rate and unimportant? No, the cause is much more serious.

If the dispatcher has to remote-control a group of pumps drawing water from the river, it would be too expensive to connect each pump with the control desk. There must be one line with a system of switches at both ends: at the dispatcher's desk and the pumping station. These switches will make it possible to receive signals from every pump in turn and send them commands whenever necessary.

These switches—step selectors and numerous relays—were the weakest spot of remote control. Switched on and off incessantly, the contacts wore off and had to be replaced almost weekly, and the whole system had to be inspected each few days. No engineer on duty was necessary, but a skilled electrician or even a trained specialist was required. Remote control was used mostly at large power plants or factories.

A new system of remote control was recently introduced in the town water mains of Orel, U.S.S.R. It was developed by local designers in co-operation with a research team from the Central Research Institute of Comprehensive Automation. The head of the team, V. Y. Khazatsky, showed us the cell of the new switch. Basically, the cell is a transistor, a wafer the size of a baby's nail, and still smaller ring, wound with a very fine wire. Next to it Khazatsky laid the same ring without wiring. Black, apparently made of metal and very light, the ring was extremely small but it was this ring that really mattered.

The ring is the armature. With the winding it makes up a midget electric magnet. Not an ordinary magnet, though. The wiring actually consists of several different coils acting as contacts of an ordinary switch. A current pulse in one coil magnetises the armature which excites the current in the other coil, just as in any transformer, while

the transistor amplifies this new pulse of current. Each cell corresponds to a definite pump, and they are switched on in turn, just like the contacts of the conventional step selectors.

This contactless switch can operate faultlessly up to 30 years without inspection or maintenance. Apart from dispensing with employees engaged in monotonous and unproductive work and thus yielding a considerable saving, this system makes the control more accurate and reliable. The entire gas system in Kuibyshev, and later in many other towns, will be telecontrolled before long.

Those wonderful rings used for the switches are magnetic semiconductors which appeared only several years ago.

FOR THE FIRST TIME IN MILLENIA

Three thousand years ago ambassadors from the country Yuyeh-Chang—as Viet-Nam was called at that time in China—arrived to pay their respects to Cheu Kung, the emperor of China. On their way home the ambassadors lost their way and came back to the capital of China, Lo Yi. Then Cheu Kung presented chariots to them. On the front butt of each chariot there was a small box with a freely rotating wooden figure of a Chinese always pointing south. This figure was called Chi Nan, which means the "index of the South" in Chinese. After that the ambassadors reached home without any detours.

Two thousand years later Chi Nan turned into Chihnanchen, or, the arrow pointing south. That was when Europeans first learned about the magnetic compass.

In ancient Greece and Rome, magicians manipulated with magnets—pieces of iron or magnetic ore. Plato wrote delightedly about the magnetic stone "which, apart from attracting rings of iron, imparts to them its power to do the same. Thus the Muse inspires poets, they impart their inspiration to their listeners and the communion of the inspired is created...."

It has been believed from time immemorial that there is a certain affinity between magnets and iron objects. The magnet was called the "loving stone" and the French for the magnet is *l'aimant* from the verb *aimer*, to love.

For thousands of years magnetism remained an enigma and the magnet was used for indicating north and south. A little more than a hundred years ago, when the connection between magnetism and electricity was revealed and the development of electrical engineering began, the physics of magnetism made rapid headway and magnets were put to all sorts of use. They were produced, however, from the same metals: iron, cobalt, nickel and their alloys. This is why these metals are called ferromagnetics, deriving their name from their chief representative, iron, or *ferrum* in Latin.

Today they abandon the field to new man-made materials. It is from these that the amazing rings Khazatsky showed us were made.

SUBTLEST OF ALL SUBSTANCES

Pour alcohol mixed with fine iron powder onto a polished piece of steel and study it through a microscope and you will see something interesting. The powder will not spread over the metal surface uniformly, but will collect along certain lines tracing, as it were, the poles of tiny magnets. This experiment is not unlike the one we saw at school: a magnet under a piece of paper with iron filings spread over it.

Now what sort of magnets are these, inside the piece of metal? To answer this question, scientists had to penetrate into the innermost depths of matter. Aptly enough, Mikhail Lomonosov, the great Russian scientist of the 18th century, called magnetism the "subtlest of all substances".

A magnetic field arises around a live wire. There are currents, too, in a permanent piece of magnet made of

steel. An innumerable host of electric charges moves within it all the time.

And not in steel alone. In any substance electrons revolve around atomic nuclei. Since any motion of electric charges produces a magnetic field each atom has its own magnetic fields.

Apart from moving around the nuclei, sometimes, at a speed of hundreds of kilometres a second, each electron also spins on its axis.

We have spoken about the complexity and diversity of the properties of the electron, a tiny particle of matter possessing wave properties. Now we should add that this particle produces different magnetic fields. Scientists have studied the ingenious motion of an electron and even determined the comparative effect of its rotation around the nucleus and its spin on its own axis.

The electron orbit is something like a ring of wire with current flowing through it. So *it* acts as one tiny magnet, and the spinning electron is another. If there are many electrons in an atom we can picture it as a beam of infinitesimal magnetic needles.

There are substances in which these needles are directed towards each other and all electron magnetic fields are cancelled. The atoms of such a substance, called diamagnetic, do not manifest magnetism.

In other substances the needles are so directed that the electron magnetic fields are not cancelled and each atom becomes a magnet. It can be designated by a larger magnetic needle since all electron fields add up to make one atomic field. Substances with such atomic fields are known as paramagnetics and ferromagnetics.

In a paramagnetic the positions of atomic magnets are chaotic. When this substance is placed into an external magnetic field all atoms tend, just like a compass needle, to turn in the direction of the line of force. The north poles of the atoms turn to the south pole of the external magnet and the south poles to the north one. Because of thermal

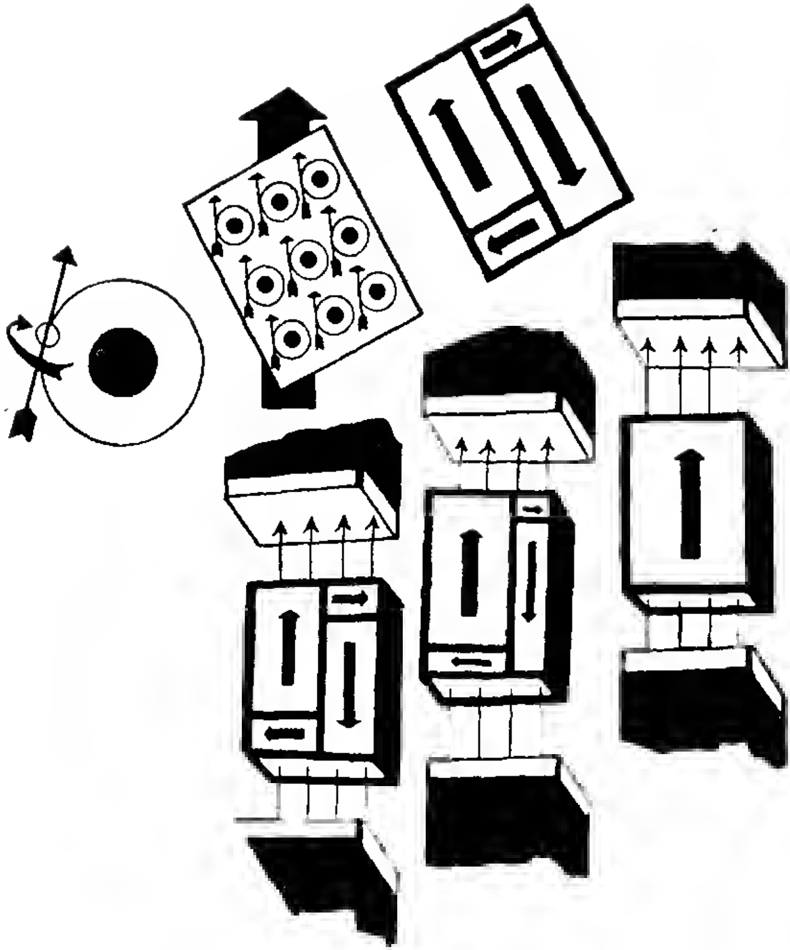
agitation, however, they oscillate all the time and therefore only a small portion of them fall into line. A substance of this kind magnetises very weakly.

Ferromagnetics alone make magnets and, to use Plato's phrase, "impart their power" to other no less "magnetic" bodies. Their atoms always cluster in large groups. Each group consists of millions of atoms and they have the same position, one and all. These groups or regions of spontaneous magnetisation, known as domains, are delineated by iron filings mixed with alcohol.

Thermal agitation cannot destroy the domains because of special electric forces at work between the atoms of a ferromagnetic. True, atomic motion intensifies as the temperature rises and the domains disintegrate eventually. The ferromagnetic becomes a paramagnetic. This phenomenon was discovered by the great French physicist Pierre Curie and the critical temperature has since been known as the Curie point. For iron it equals 768° C.

Incidentally, the principal magnetic properties of ferromagnetics depend solely on the axial rotation of electrons—but not all of them. Out of the 26 electrons of an atom of iron only three participate in "ferromagnetism" and of the 28 electrons of nickel, only one. The spontaneous reciprocal magnetisation of these electrons in adjacent atoms stems from the electric forces at work in the ferromagnetic.

When a substance of this kind gets into a magnetic field its domains, situated at random, turn and the substance becomes magnetised. More accurately, the domains do not turn, but merely absorb each other. The domain directed along the lines of force of the external field grows at the expense of its neighbours. The fact is that the borderland between the domains is a layer 100 to 1,000 atoms thick, and the magnetic fields of these atoms pass smoothly from the direction of one domain to that of another. First the atoms closest to the growing domain turn and so the borderland shifts outside. Next atoms turn, etc.



Top: an atomic magnet, the formation of a domain and a piece of a ferromagnetic consisting of several domains. *Below*: this piece is magnetised in an outer magnetic field, the domain orientated along the outer field growing at the expense of its neighbours

The process is rather rapid and the borderland between the domains moves at a speed of scores of metres a second.

The field of the domains adds to the external field and intensifies it many times. This is why iron cores are put within coils when electric magnets are made. A coil without a core will also work as an electric magnet, but the core increases its power thousands of times. For the same reason iron cores are used in transformers, in the stators and rotors of electric motors, or in coils in broadcast receivers.

A solid iron core, however, is suitable only for direct current. Alternating current produces a changing magnetic field. Let us recall that current is induced whenever a conductor crosses magnetic lines of force. The result is the same if the conductor is motionless, but the field changes. Now, the armature is also a conductor and currents are naturally induced in it.

These eddy currents (discovered by the French physicist Foucault and hence known as Foucault currents) are at work within the armature, heating it and absorbing much energy. Besides, they produce their own magnetic fields directed against the principal field and demagnetising the armature. The higher the frequency of the winding current, the more frequently the field changes and the larger the amount of energy wasted in the armature.

To weaken the eddies the armatures of alternating current electric machines are made of thin iron sheets isolated from each other. The armatures of high-frequency radio transformers are made of iron powder mixed with some insulating substance. These measures increase the electric resistance of the armatures, but worsen their magnetic properties and make them more expensive. And when the highest frequencies have to be dealt with in radio engineering no amount of ingenuity can make iron armatures suitable.

The way out was to search for new materials, no less "magnetic" than iron, but highly resistant electrically. It is among semiconductors that these materials have been found.

PEACEFUL AND DISORDERLY "TENANTS"

New semiconductive ferromagnetics known as ferrites conduct electricity millions or even thousands of millions times worse than iron, cobalt and nickel. But the chief advantage is that the conductivity of ferrites can be controlled, though differently than in germanium or silicon: since ferrites have a different structure, the flow of current in them is different.

Like thermistors, ferrites belong to oxide semiconductors because they consist of metal oxides. In a crystal of pure germanium or silicon the atoms cling to each other and each of them keeps all of its valence electrons, but crystalline metal oxides are built differently. The atoms of the metal give their outer electrons to the adjacent atoms of oxygen and become positively charged ions. The atoms of oxygen for their part receive the excess electrons and become negative ions. It is the reciprocal attraction of the oppositely charged ions that keeps the crystal together.

Imagine billiard balls arranged into a triangle before the game. Suppose we put another layer of balls on top, and still another on top of the second layer. The balls of each layer, except for the lowest, will sit in the hollows between the balls below. This is how ions of oxygen are located in the crystals of most of ferrites and thermistors.

There are two kinds of hollows between the balls; some small and some larger. The larger hollows communicate with each other and thus form galleries or suites of "rooms", so to speak, while the smaller hollows do not. It is the latter that metal ions tenant since they are always smaller than oxygen ions.

Nearly all ferrites (the exceptions are very rare) contain ions of at least two metals. The properties of the

material essentially depend on which of the two have tenanted the larger "rooms" and which the smaller ones. Besides, many "rooms" are vacant, since there are at least twice as many of them as the "tenants": the metal ions.

The major feature of ferrites is that their metal components have different valences. We have mentioned what that means: the outer shell of an atom may have different numbers of valence electrons; that is, electrons participating in the binding with other atoms. Ferrites usually contain the oxides of trivalent iron and some bivalent metal: nickel, zinc or lithium.

Oxygen ions firmly hold the electrons they have captured, and so only metal ions can exchange charges in such a crystal. Yet the "tenants" in the smaller "rooms" are so far away from each other that electrons cannot leap between them easily. These are quiet and secluded "tenants".

The exchange of electrons is quite possible, however, among the "tenants" of the larger "rooms", forming suites. True, the transition is more difficult if ions of different metals alternate in such a suite.

It may also happen that all larger "rooms" have been occupied by ions of a metal which may change its valence, such as iron, titanium and manganese. Let us suppose that ions of bivalent and trivalent iron alternate in a suite. These are restless "tenants" because they exchange electrons even from thermal agitation. If a battery is connected to such a crystal, electrons will begin to jump from ion to ion, mostly in one direction, and thus produce a current.

Sometimes it is this structure that is needed. For example, many thermistors must have fairly high electric conductivity. The purpose is, therefore, to tenant the larger "rooms" with ions of variable valence metals to ensure the free passage of electrons.

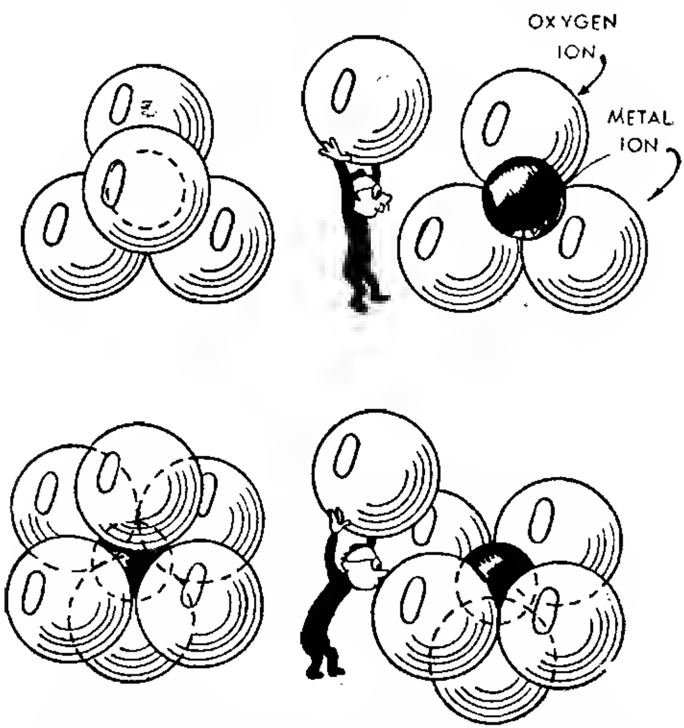
In ferrites this property is impermissible, however. These materials should, on the contrary, possess the highest resistance possible, millions of times higher than

any thermistor. Incidentally, this is why the natural ferrite of iron, the common loadstone, is not suitable for armatures: it conducts current too well.

PAIR OF INSEPARABLES

The magnetic properties of ferrites can be controlled as well.

If a piece of pure iron is placed into a magnetic field, the metal is magnetised. The domain structure, however, disintegrates once the piece is removed from the field. This is why iron is no good for making permanent magnets.



In ferrite and thermistor crystals there are two kinds of "rooms" formed by oxygen ions and occupied by smaller metal ions

Steel can be magnetised in a stronger field, but it preserves residual magnetism after it is removed from the field. The domains in steel are "lazy": they do not obey at once when the steel is magnetised and they do not fall out of magnetic lines when the field is removed. The explanation is that steel is heterogeneous. Apart from iron, it contains particles of carbon and other nonmagnetic inclusions. These settle on the borderland between the domains and reinforce it, so to speak. This is why permanent magnets are made of steel which is of no use for the armatures of alternating current machines since these must remagnetise rapidly and easily.

Ferrites for armatures should be magnetically soft and those for permanent magnets magnetically hard. Powder metallurgy technique is used in the manufacture of ferrites and their properties, therefore, depend on the composition of the powder, the temperature and duration of the baking, etc. The effect of all these factors has been studied thoroughly and many new ferrites have been created at the laboratory headed by G. A. Smolensky, Dr. Sc. (Phys.-Math.), of the Institute of Semiconductors.

There are ferrites which preserve magnetism for a long time and easily remagnetise, if necessary. They are used, for example, for the "magnetic memory" of electronic computers. True, metal ferromagnetics are also used for the "magnetic memory", as magnetic tape or drums which magnetise and store the signals thereby. But semiconductor ferromagnetic ferrites excel in this role.

Thousands of tiny, scarcely visible ferrite rings over the criss-crossing wires of a net the size of a postcard can replace an expensive, fragile and cumbersome cathode-ray tube. Ferrites take up very little room, save electric energy and improve the reliability of computers. It is precisely from these ferrites, though somewhat larger, that contactless relays for automation and remote control are made.

Ferrites are especially valuable in radio engineering. We have described how printed circuits came into being. This is where tiny ferrite cores proved useful. And ferrite can well replace the conventional loop aerial, for example. Thus the latest Soviet portable models employ printed circuits, ferrite aerials and cores.

The armatured coil in the set is always accompanied by a capacitor. This pair makes up an oscillation circuit without which neither transmission nor reception is possible. When we tune in the receiver to a certain wave band we, often unaware of it, change either the capacity of the capacitor or the induction of the coil.

In other words, the manufacture of small radio sets involves the designing of very small capacitors concentrating electric power.

Semiconductors stand us in good stead in this field as well.

THE FOURTH AND THE LAST

A major drawback of radio stations became evident when the Second World War broke out. Whenever weather changed their performance dropped, tuning became more difficult and communication failed. True, these faults had been observed before but in 1941 they became especially conspicuous and had to be eliminated as quickly as possible.

The main culprits were capacitors. The simplest capacitor consists of two insulated metal plates. The capacitor builds up an electric charge to discharge it at the desired moment. To increase its capacity, i.e., its ability to store more electricity per dielectric, a piece of paraffin-impregnated paper is placed between the plates. The layer increases the capacitance of a capacitor just like an armature intensifies the magnetic field of a coil.

Such "sandwich" capacitors, or rather their components, react differently to heat and cold. As the temperature changes cracks and hollows appear in the capacitor, its

capacitance fluctuates and the operation of the entire radio station is disrupted. So capacitors of constant capacitance had to be developed.

The problem was tackled by a team of physicists of the P. N. Lebedev Physical Institute of the Academy of Sciences of the U.S.S.R. The team was headed by B. M. Vul who was a young scientist at that time and is now Corresponding Member of the Academy of Sciences of the U.S.S.R. Obviously, the new capacitors had to be made of ceramics—that was the only way of fusing together both electrodes and the insulating layer between them. Needless to say such capacitors were produced. The method is simple and differs little from the production of ferrites. Only one new operation is added: special paste containing silver is deposited on a ceramic plate or tube and at a temperature of several hundred degrees the metal fuses with the ceramic and forms a thin electrode film on its surface.

What should the ceramics be made of was the first question scientists had to answer. First of all Vul recollected the days when he undertook his post-graduate course. His assignment was to study titanium dioxide. This substance, and especially one of its crystalline varieties, rutile, is an excellent insulator.

The quality of the insulator is determined above all by permittivity showing how many times the capacitor capacitance increases when the air gap between its plates is filled by a certain dielectric. The larger the factor the better the insulator: for air it equals unity, for paper two and for glass five. For rutile it comes up to a hundred.

Rutile itself was no good for manufacturing capacitors since it could be baked at extremely high temperatures. So the scientists combined rutile with other substances, and in particular, the oxides of magnesium and calcium. The resulting salts of titanic acid, magnium titanate and calcium titanate, had permittivity of 15 and 150. The permit-

tivity of one compound increased with temperature while the other decreased.

The mixture of these two salts was used to manufacture condensers with permanent capacitance. It was a great victory, all the more so since the research was carried on in the difficult conditions of war evacuation. The new capacitors quickly went into extensive production and the research seemed to end there and then. Actually, this was just a prelude to a great discovery.

On their return to Moscow in 1944, Vul and his associates decided to continue the research and first of all to inquire into the causes of the difference between the properties of magnesium and calcium titanates. The difference seemed to be connected with the sizes of the ions of these crystals: the ion of calcium is larger than that of magnesium and the permittivity of calcium titanate is also larger.

Both metals occupy the second group of Mendeleyev's Table, calcium holding a lower place since it is heavier and its ion is larger. Now what about other metals of the same group, still heavier and with larger ions? The next element, strontium, was tried and a substance with a permittivity over 200 was obtained. So the idea was correct. But there was still another—barium.

And so the fourth and last titanate, barium titanate, was obtained. All research workers of the laboratory eagerly awaited the results of measurement and it was incredible—the figure exceeded a thousand!

A few years later another remarkable property was detected in barium titanate. But let us first outline the events which preceded the discovery of this new semiconductor.

DANGEROUS RECORD-BREAKING

Twenty-five years ago Soviet Academician I. V. Kurchatov together with his associates studied Rochelle or Seignette salt, discovered by the Frenchman Seignette nearly than 300 years ago. The Soviet scientist found that

the permittivity of the salt was tremendous, though the effect was observed at temperatures no higher than $+24^\circ$ C. Apart from this limitation, the crystals of the salt were very unstable and readily absorbed moisture, all of which complicated the practical use of the salt.

Two more substances with the same extraordinary properties were discovered later on, but in them these properties were manifested only at very low temperatures. Finally, barium titanate was added to the list.

What was the explanation of the surprising properties of these substances? Why were I. V. Kurchatov's studies of seignette salt so important in the development of the physics of solids?

Atoms and crystal cells can be electrified just as they can be magnetised. In other words, charged particles (ions in a crystal) shift with respect to each other, that is at least some of the ions are asymmetric and the "centres of gravity" of positive and negative ions making up the crystal cell do not coincide. Such a crystal cell has two electrical poles, positive and negative, and is known as a dipole.

Many substances have a similar structure. Yet in an overwhelming majority of them dipoles are scattered at random and range in a certain order only in an electric field; between condenser plates, for example. In some crystals, however, dipoles are collected in large groups which are called domains, just as groups of atomic magnets. The intradomain structure is permanent and they merely turn in an electric field.

So we have something similar to ferromagnetics in a magnetic field. This is why such self-electrifying substances are sometimes called ferroelectrics, or more often seigneto-electrics after their representative No. 1, seignette salt. They stand out among dielectrics and semiconductors like iron, nickel and cobalt among metals.

Obviously they can be used to make capacitors with an enormous capacitance or small condensers with the

same capacitance possessed by the conventional large capacitors. This is why the discovery of barium titanate was such a major event. This substance was admirable in practice: its manufacture was simple and durability enormous. Besides, barium titanate is moisture-proof: it can lie in water without harm and, what is even more important, preserves its valuable ferroelectric properties up to $+125°$ C.

True, it cannot stand very high electric voltages, but that is of no importance in fields such as radio engineering. Splendid capacitors for midget radio apparatus are made of barium titanate; in particular those in which printed circuits are used. As powder, it is added to rubber and plastics to improve their insulatory properties.

Following Vul's discovery seigneto-electric research made rapid headway in many countries. In the U.S.S.R. G. A. Smolensky, Dr. Sc. (Phys.-Math.) and his associates discovered several new valuable ferroelectrics.

The new materials are gaining ground. They are used as the "electric memory" of electronic computors just as ferrites are used for their "magnetic memory". An electric pulse to be stored or "remembered", charges a capacitor and the pulse is "read out" whenever necessary (i.e., the capacitor is discharged).

Barium titanate and other ferroelectrics are used to manufacture nonlinear capacitors, with capacitances strongly dependent on voltages. If the voltage across the capacitor changes, its capacitance increases (or falls) very steeply sometimes. Such capacitors are used instead of electronic tubes or transistors as radio amplifiers capable of intensifying the power of a signal millions of times.

Ferroelectrics have yet another major feature: the capacitance of capacitors made of them depends both on temperature and on tension. A shortcoming in some cases, this property makes it possible to manufacture various thermometers. These are especially sensitive within a comparatively short range. We have said that barium titanate preserves its ferroelectric properties up to 125° C.

But close to this temperature its capacitance as a capacitor can increase several times as its temperature rises merely one or two degrees. Barium titanate increases its permittivity until it reaches a record value at 125° C over 6,000. But the record is dangerous. A few more degrees and the record-breaker is disqualified: the domains of barium titanate are destroyed if the temperature continues to rise. Like ferromagnetics ferroelectrics have a certain Curie point.

There are substances, however, which can replace barium ferrite and titanate at temperatures above the Curie point. It appears that ferromagnetics and ferroelectrics have their own antipodes, called antiferromagnetics and antiferroelectrics. Their elementary magnets and dipoles are paired in domains, the pairs directed against each other, and so the fields are neutralised. They therefore make very poor magnetic and dielectric materials. But as soon as the Curie point has been crossed the order is reversed and they become ferromagnetics and ferroelectrics, opening now possibilities in engineering.

We have come across something similar in thermistors and semiconductor thermocouples. All these devices are usually built with materials preserving their valuable properties up to 300° C or 500° C. At higher temperatures they can be replaced by new semiconductors which behave like insulators at normal temperatures.

As we described the processes at work in barium titanate at a temperature of 125° C we did not look inside the crystal and did not mention still another of its wonderful features.

FIRST A CURIOSITY, THEN A NEW FIELD

One ship after another sank on the high seas soon after the outbreak of the First World War. The culprits, German U-boats, were invulnerable and invisible as they continued to strike new blows. The government of France

appealed to scientists to find a method for detecting enemy submarines. Many researchers had tackled this problem and failed until well-known physicist Paul Langevin came out with his proposal.

His idea was to use the phenomenon discovered by Pierre and Jacques Curie in 1880. If a plate is cut in a certain way from a crystal of quartz or rock crystal and placed between two metal electrodes it will acquire remarkable properties. When it is compressed one of its electrodes is charged positively and the other negatively. When the plate is stretched, the charges are reversed. This phenomenon was named piezoelectricity from the Greek word *piezein* which means "to press". Soon the Curie brothers discovered the reverse effect: when charges were applied to the facets of the crystal it contracted or stretched.

For a long time this phenomenon, just as thermoelectricity, was regarded only as a scientific curiosity. Forty years later Langevin, a pupil of Pierre Curie, found the first application for this effect.

First he built an apparatus for "percussing" water. Sound waves travelling in the water pressed the plate of quartz at regular intervals, making it oscillate, as a result electrical charges appeared and disappeared on the surface of the plate and were picked up by a radio receiver or oscillograph.

Then Langevin improved his apparatus so that it radiated waves and received echoes bounced off ships. These were ultrasonic waves, with a very high frequency of oscillations and therefore inaudible. These rays can be beamed in the desired direction over large distances in a dense substance.

A crystal of quartz was also the ultrasonic oscillator in the Langevin apparatus. Connected to the electric power mains, the crystal will contract fifty times and expand as many times. Its oscillations transmitted through the air will be perceived by our ear as a definite sound. If, how-

ever, a high-frequency tension, over 20,000 oscillations per second, is applied, we shall hear nothing: the quartz will radiate supersounds.

These inaudible sounds were sent through water in short pulses and the echo was timed. Given the speed of the sound and the time it travelled to the target and back, it was not difficult to determine the distance to the enemy submarine.

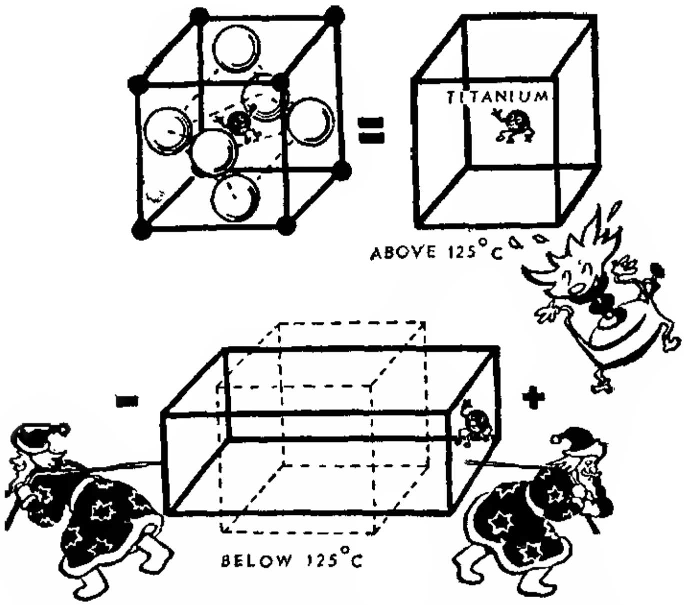
Langevin's pioneering work has since developed into a large independent field known as piezoengineering. Not quartz, but barium titanate is now used as an ultrasonic radiator, for it proved to be a piezoelectric material as well. Barium titanate costs one-hundredth of what quartz does. It is a good example for illustrating the origin of piezoelectricity. At the same time we can now give a more elaborate answer to the question: "What happens to a barium titanate semiconductor as its temperature reaches the Curie point?"

The cell of barium titanate crystal, "titanate's house", is very much like the "larger room" in the ferrite crystal: it is also composed of six oxygen ions with a titanium ion inside. But the "house" is too spacious for this ion: the "tenant" can move about or can lean against one of the walls and stay at rest. As it happens the property of the crystal depends on the behaviour of this ion, which changes at 125° C.

At high temperatures the thermal agitation energy of particles is so intense that the "tenant" becomes restless and begins to jump from one wall of the "house" to another. As a result the ion's mean position proves to be at the centre of the "house": the crystal cell does not become a dipole.

Now, at temperatures below the Curie point, the thermal agitation energy is not sufficient to pry the positive ion of titanium off the negative ion of oxygen: the "tenant" clings to one of the walls. In other words, the ion of titanium is situated off the centre and the cell is a dipole. The

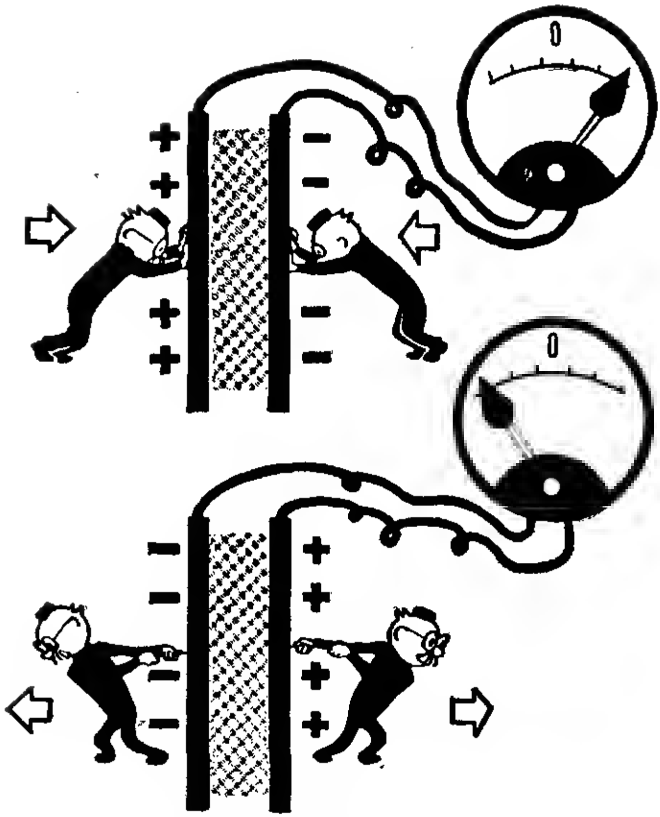
"tenant", a clumsy heavyweight, leans against the wall and the house stretches out in that direction. The same happens in the neighbouring cell-"houses", since all "tenants" act in unison clinging to the same side. Domains are formed as a result.



125° C is the breaking point which changes the behaviour of the titanium ion in the crystalline cell of barium titanate. The "tenant" either keeps jumping from wall to wall, its mean position being at the centre of the cell, or rests against one of the walls. As a result the cubicle bulges and electric charges spring up at its ends: the cell becomes dipole

When all "houses" stretch out in one direction, the crystal is like a large dipole: opposite charges appear on its opposite sides.

These charges attract the charged particles always present in air or water. These stick to the sides, neutralise their charges, and form a double layer: the positively



How piezoelectricity originates

charged layer coated with negative particles, and the negatively charged layer with positive particles.

Whenever the crystal is compressed, its polarisation weakens, the original charges of the sides decrease and part of the outer charges becomes free. If the crystal is stretched, the polarisation increases, and opposite uncompensated charges appear again in the double layer. This is how electricity, named after the Greek word *piezein*, originates.

But even when the crystal is neither compressed nor stretched the shape of the dipole "houses" does not remain constant: it reacts to the changes in temperature and electric tension. The colder the crystal, the greater the stretching of the "house". In an electric field the ions also shift: the cells are stretched or compressed depending on the direction of the field. This occurs not only in barium titanate, but in seignette salt as well.

It is noteworthy that in this respect ferroelectrics can be compared with ferromagnetics. Iron, nickel and cobalt are also capable of changing their dimensions in a magnetic field. This effect, known as magnetostrictional from the Latin word *strictus* which means "compressed", is usually very slight and is reduced even more when other magnetic properties are brought out. But sometimes this effect is useful.

In nickel, for example, this effect is much more appreciable than in iron. If an alternating current of high frequency flows through a wire wound around a nickel rod, the latter compresses and stretches out with the same frequency. Of course, the increase and decrease of its length is minute, but quite sufficient for radiating ultrasound waves. There are alloys in which this effect is still stronger: magnetostrictional ultrasound radiators are made of these alloys.

True, the frequency of their oscillations is still limited, and therefore piezoelectric oscillators (and receivers) of barium titanate are mostly used for that purpose.

ON EARTH, IN THE SKY AND ON THE SEAS

It has long been noticed that dogs hear sounds man cannot hear. Incidentally, when a poacher wanted to call his dog without giving himself away he used a special whistle which produced waves of so high a frequency that only the dog could detect them.

This inaudible whistle is now used in coal mines, an electric-car operator being the "hunter" and a point switching mechanism the "dog". The operator switches on his ultrasonic siren as he goes and thus opens the way.

Depth-ranging ultrasound also warns a ship's captain about shallows. Just as in the Langevin apparatus, supersounds in this case are not radiated continuously, but in short powerful pulses. But now there is no need of registering its travelling time by a watch. When the pulse is sent out the first peak of a green wave appears on the oscillograph screen. When the sound is picked up by the receiver on the rebound off the bottom, another peak appears, and the distance between the two peaks calibrated in metres shows the depth.

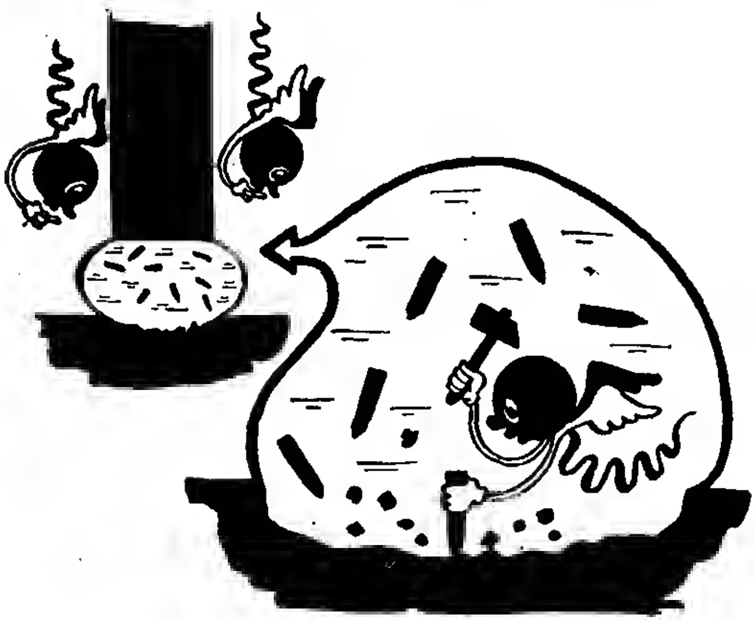
The same two peaks can be seen on the screen of the ultrasonic defectoscope checking large machine parts for faults. The first peak appears when the ultrasound pulse enters the part and the second when it is reflected off its bottom. But a third peak may intervene, meaning that a cavity lurks somewhere within the metal. The third peak reports its location and size.

Nor is ultrasound a mere industrial checker.

When we described the production of transistors at a radio plant we barely mentioned the sawing of the monocrystal of germanium into small sections. Yet this is one of the most involved operations. A solution in which grains of a very hard abrasive substance are suspended is poured over the ingot. Steel tapes moving across or along the ingot use these grains to cut the germanium.

Using this technique the crystal can be cut into plates which are three times as thick as is necessary for triodes. It is impossible to cut them thinner without crumbling them since germanium is very fragile. This is why the cutting is followed by polishing and then pickling. As a result two-thirds of the germanium is scrapped and reprocessed. And this is superpure germanium which has consumed so much time and effort!

But imagine a different picture. The same steel tape, but much thinner, is connected to a piezoelectric plate. Powerful ultrasound oscillations are transmitted to the same grains of abrasive, which scratch and scrub the crystal. The tape cuts the ingot like a knife through butter.



The vibrator's powerful ultrasound oscillations agitate abrasive grains grinding and gnawing the metal

Though the "cutter" is essentially the same, there is much less waste and thinner plates can be sawn.

The new method is used extensively in the treatment of metals. A cutter of any shape can be used instead of the tape: appertures of a very intricate profile, which it is difficult or practically impossible to produce by conventional methods, can be made easily and quickly employing this technique. One ultrasound machine tool for processing

hard and fragile materials saves several thousand rubles a year while the machine tool itself costs about 3,000 rubles.

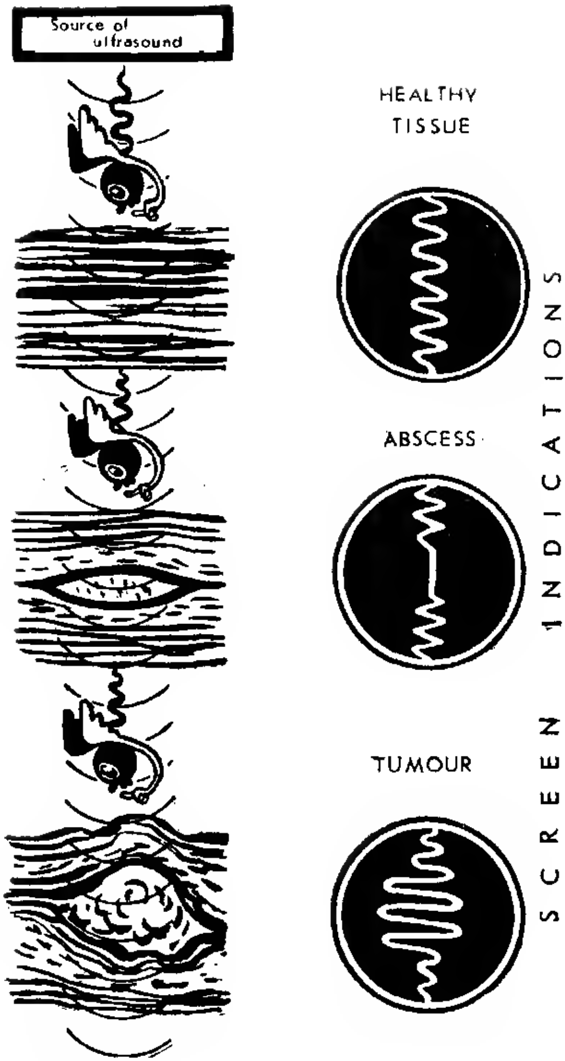
Piezocrystals also find new applications in medicine. Percussion has long been used for examining the patient: the force and tone of reflected sound enables a physician to ascertain the state of an internal organ. This is where ultrasound can be of much use since malignant tumours reflect it better than healthy tissue. A curve, helping the physician's diagnosis, appears on the oscillograph screen just as in a defectoscope or in a depth-sounder.

Ultrasound is used in many other ways. We have given just a few examples. It should be borne in mind, however, that piezocrystals are not used only for ultrasonic radiators or receivers.

Physicians and coaches can control sportsman's organism from a desk. Tiny piezo-transducers, sensitive and reliable, are attached to the sportsman's hands and chest, and a miniature semiconductor radiotransmitter to his belt. Radio signals report on the sportsman's respiration and cardiac action at various conditions.

The scalpel has also been made vocal. Now the surgeon can hear, as well as see, what he incises: the tone in the earpieces he wears changes depending on what the scalpel is cutting: a blood vessel, muscle tissue or sinews. But it is especially important to help the surgeon where he cannot see. When a wound is probed the surgeon can hear the instrument touch a solid and he can determine whether it is metal or bone by the tone of the sound. Both instruments, the scalpel and the probe, are equipped with piezo-transducers whose signals are transmitted to earpieces.

Piezocrystals serve man not only on the ground or under water, but also in outer space. Extremely sensitive piezoelectric transducers installed in high-altitude rockets and artificial Earth satellites can detect the minutest meteoric particles, with a mass of a thousand-millionth of a gram.



The ultrasound tumour detector is a physician's new aid. Healthy tissue, an abscess and a malignant tumour reflect ultrasound differently

Today engineering sets new demands on piezoelectrics: their temperature resistance has to be improved. Attempts are being made to create new ceramics, after the pattern of barium titanate, with a high Curie point. Proceeding from the structure of barium titanate, substances are selected to replace titanium, or perhaps barium, in the magnitude of ion charges, so that the ferroelectric properties of the substance survive at possibly higher temperatures.

Ferroelectrics with a Curie point close to 500° C have already been obtained. True, they are worse than barium titanate in other respects, but when introduced into ceramics they raise the temperature limit of capacitors and piezoelements. Since the trend of the research seems to be correct, it will no doubt be successful.

Finally, there is an opinion that materials which could be both ferrites and ferroelectrics can be produced artificially. The practical aspects of this idea are still vague but the prospects it holds out are unquestionable. Ferrites, ferroelectrics and piezoelectrics mark three victories for semiconductors in fields where the domination of metals and classical dielectrics seemed unchallenged.

DEATH AND BIRTH OF PHOTON

IS THIS THE WAY?

Surely a photon cannot die before its birth! Obviously, the title must be "birth and death" and not "death and birth".

No. This is no mistake: one photon dies and another is born in its place.

"*Le roi est mort, vive le roi!*" Thus his subjects greeted a new French king before his predecessor was buried. One succeeded another immediately.

This is not quite the case with photons. Mr. Photon Junior does not appear until some time after the death of Mr. Photon Senior.

Now how does one photon disappear and how is another born?

To answer the first question is easy: one of the phenomena attending the disappearance of a photon is well known to us. Let us recollect a photoresistor which in-

creases its electric conductivity by absorbing light. A photon or a quantum of light, the elementary portion of radiation, is absorbed by the atom it encounters. The energy of the valence electron increases in the process, and off it rushes through the crystalline lattice, leaving a hole behind.

The electron travels from one lattice point (an atomic nucleus surrounded by electronic shells) to another within the crystal. Finally, the electron encounters a hole in one of these shells and settles in the new place.

Let us also recollect the description of the "valley" and the "hill". The recombination of holes and free electrons heats one of the junctions of a thermoelectric cell. The energy spent on the disengagement of the electron and the production of the hole is thus released.

Much the similar takes place in the photoresistive cell. True enough, in most cases heat is released during the recombination. There are semiconductors, however, in which the recombination of two types is possible: thermal and luminous. In the latter the combination of a hole and a free electron produces a photon. Not the one that has disappeared; it is quite different from its predecessor. But still this is a quantum of light and the substance which has absorbed it begins to glow.

We have all seen such substances many times because they have become quite common. They are known as crystalline phosphors or, simply, phosphors. They include some of the substance used for manufacturing photoresistive cells, such as cadmium sulphide, zinc sulphide and calcium sulphide. At any rate phosphors must be photoconductive, that is, they must be able to absorb light and release electrons.

Phosphors emit a cold glow, like glow-worms, deep-water fish, rotten stumps or decaying fish whose luminescence was described by Aristotle. The cold glow may have different causes. Not all kinds of luminescence are like the one observed in phosphor semiconductors. Yet nearly all phosphors used in practice *are* semiconductors.

We have not answered the second question: "How is the new photon born?"

When the conventional photoresistor is shaded, the current in it weakens or disappears altogether. The hole-electron recombination ceases simultaneously, to all intents and purposes.

In phosphors this recombination is prolonged: they sometimes give off stored light for several hours. During the war blackouts, passers-by wore luminescent discs on their hats or lapels. Zinc sulphide (or another compound) in these discs absorbed light in the daytime and returned the stored energy in the form of light at night.

It appears that an electron released by a photon is sometimes captured again: it gets stuck in all possible dislocations of the phosphor crystalline lattice.

Thermal agitation, the oscillations of the crystalline lattice points, can supply the energy necessary to release it. Not all electrons, however, get released from their captivity at once. That is why the light stored by the phosphor is emanated gradually. The duration of this afterglow varies with material and depends on the properties of the substance, on the "depth of the pits" into which electrons fall.

Finally, the electron is released. Now it is free to choose two paths. Either it will encounter a hole in one of the semiconductor atoms and having combined with it, release some heat, or. . . .

At this point we must say that phosphors always contain metal impurities in small quantities, just a fraction of one per cent. Zinc sulphide is doped with copper, for example. Copper atoms are known to part with electrons easily. Some of these electrons get into the pits at the top and some come across holes in the semiconductor and fill them. As for the copper atoms, they become positive ions.

If a free electron carrying the energy of the lost photon encounters such an ion, a new photon may be produced in the process of recombination. Thus, the ions of copper, called the activator, become the centres of glow.

Now why this is so and why there is glow only when free electrons bump into activator ions (and not always even then) is still not clear. In general, luminescence is one of the most intricate problems of physics. So far there is no general theory of crystalline luminescence, though this phenomenon has long been known and has been studied for more than a century. This is what the Soviet scientist E. I. Adirovich, Dr. Sc. (Phys.-Math.), writes about this problem in his book on luminescence:

"In the 350 years since the discovery of crystalline luminescence, physics and chemistry have on the whole come from the mechanics of Aristotle to the mechanics of Einstein, from alchemy to the conversion of elements in nuclear reactions and from the search for perpetuum mobile to the use of nuclear energy. During that time only a few steps were taken towards the understanding of the mechanism of crystalline luminescence."

Of course, even these steps show that luminescence is a much more complex phenomenon than we have described it. It could be added that apart from the afterglow (or phosphorescence) a short-time glow (or fluorescence) is observed when light is absorbed. The explanation is that some of the released electrons combine with the ions, the centres of glow, immediately, bypassing the pits on the tops. On the other hand, the path of an electron after it has been dislodged from the pit may be much longer: it may, sometimes repeatedly, stick to the lattice defects—get into another pit, etc. Apart from the impurity ions (as copper in zinc sulphide), the ions of the metal of the semiconductor, zinc in the present case, may become the glow centres. Excess atoms of zinc are also capable of becoming the same. Therefore, pure zinc sulphide can glow without any activators.

Yet even with these additions our description is very rough. Nor shall we try to make it more specific. We shall merely point out that the research conducted by the late S. I. Vavilov and his school have been of exceptional importance in the study of this problem. It paved the way for the practical use of phosphors, in particular in fluorescent lamps.

THE DIFFERENCE BETWEEN PHOTON JUNIOR AND PHOTON SENIOR

Fluorescent lamps are quite common nowadays. We come across the long glass tubes radiating "daylight" everywhere: in the underground, in shops, streets and apartments. Wires are attached to both ends of a tube and a current flowing through the gas in the tube makes it glow.

The gas is a mercury vapour. If we saw the luminescence of this vapour, the light from these lamps would be very weak and have an unpleasant bluish or grey-greenish hue. When a current flows through a gas-filled tube the gas emanates only its own characteristic rays: red, or blue, or green. Multicoloured advertisement signs are made up of such gas tubes filled with neon, argon, etc. Yet no gas can produce all colours of the rainbow, although white light consists precisely of the mixture of all these colours.

The colours of rays are different because the energies of their quanta are different. In the visible part of the spectrum the quanta of red has tbe lowest energy and those of violet rays the highest. A gas may radiate only definite kinds of quanta or sometimes even one kind only.

To make a fluorescent lamp glow white, the inside of the tube is coated with phosphor, which makes it opaque. This coating transforms the radiation of mercury vapour into a pleasant white light. By varying the composition of the coating this light can be made infinitely close to diffuse sunlight on a dull day, and so on.

There is a reason for mercury vapour being inside the lamp. The whitish light which we would see if there were no phosphor coating is only part of the radiation of the vapour and not the chief part either. Mercury vapour emanates mostly invisible ultraviolet rays.

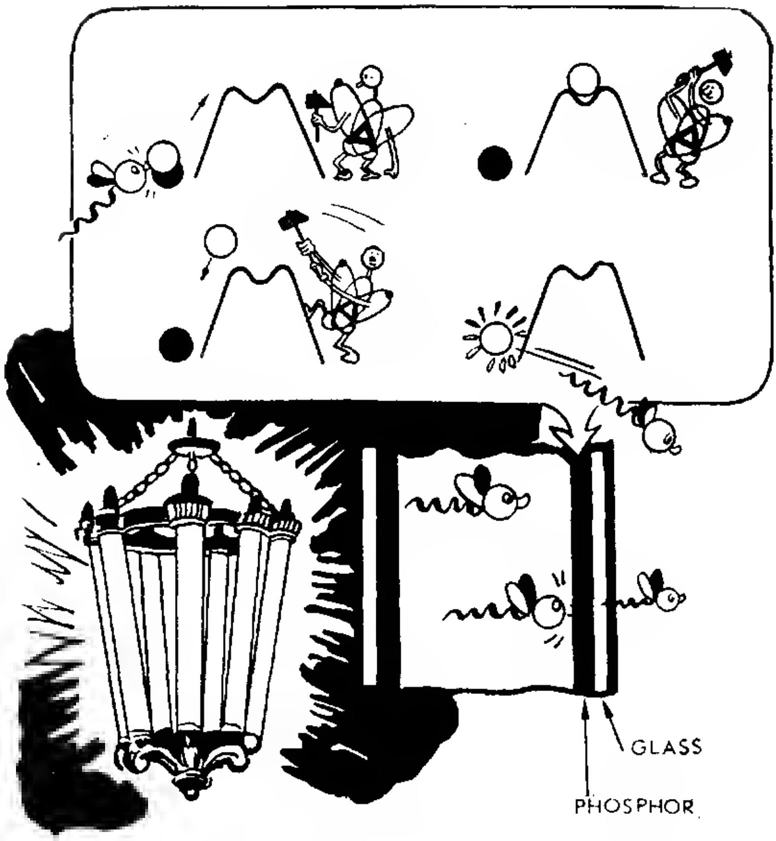
These rays are part of sunlight and they are responsible for the tanning of the skin. They are also radiated by a mercury quartz lamp. In a fluorescent lamp ultraviolet rays are absorbed by the phosphor coating which transforms them into the visible white light.

But the quanta of ultraviolet rays have a much larger store of energy than those of visible light. Where does the excess energy disappear to? Unfortunately, it is converted into heat in the phosphor itself during the thermal hole-electron recombination. This energy loss in the phosphor can be compared with friction losses in any machine.

This is why Photon Junior differs from Photon Senior. Let us note that photon annihilation and production occurs during other transformations of light as well, but it is only in luminescence that the yield of secondary photons is delayed and the "afterglow" is produced. Besides, the photons radiated by phosphor have always lower energies than those absorbed. Part of the energy is inevitably wasted during the work of this "machine". Therefore, luminescence "shifts" towards the red end of the spectrum. A phosphor can convert yellow rays only into red or orange rays and blue rays into yellow or green rays.

The only rays which can be transformed into rays of any colour are ultraviolet rays. While absorbing them, a phosphor radiates quanta of various energies. By selecting the relevant composition of a phosphor, the quanta it radiates may be made to consist of all colours of the rainbow producing white light when combined.

Despite the energy losses in the phosphor, such lamps are much more economical than the conventional incan-



Ejected by a photon from the phosphor atom, an electron gets stuck in an irregularity of the crystalline lattice: a "pit on a hill". Atomic thermal oscillations knock the electron out of the pit and a photon is recreated if the electron meets an ion of the impurity which forms the centre of glow. This is how afterglow occurs in crystalline phosphors. *Below*: a cross-section of a fluorescent lamp. Note that the photons inside the lamp are larger than outside. The explanation is that the energy of the quanta of the ultraviolet rays emitted by the vapours of mercury is higher than that of visible light, the difference in their energies being converted into heat in the phosphor

descent lamps. Lamps with an incandescent tungsten filament convert nearly all electric energy into heat. Only a few per cent of the energy is spent on lighting. If we recall that 80 per cent of the energy of the fuel is wasted in burning it will be clear that the net loss of energy when the conventional lamps are used comes up to 99 per cent.

Many countries spend thousands of millions of kilowatt-hours of electric energy on lighting and even a one per cent increase of the efficiency factor of the lamps would be a vast contribution. The efficiency factor of fluorescent lamps is higher, not by one per cent, but three or four times, because they convert all electric power into light, bypassing the stage of heat. Besides, the new lamps last several times as long as their predecessors.

These lamps have good chances of improvement. Thus, phosphors in which two quanta of lower energy could appear instead of one large quantum, may be selected. This exchange of photons would considerably decrease the losses in the phosphor.

However, fluorescent lamps are not free from shortcomings. To begin with, they are sensitive to temperature changes, especially to cold which retards the appearance of the glow. Besides, they are rather large, which is inconvenient sometimes.

But all this is temporary. These lamps are very young and their epoch has just begun.

Throughout the millennia man used all sorts of sources of light, from a camp fire to the incandescent lamps of today. But far as these are removed from each other in time and technical levels, they are kindred in the principle of obtaining light through heat, an unproductive, primitive method indeed. Now for the first time there have appeared new sources of light which need no heating, "cold light" sources. So semiconductors are revolutionising this field as well.

A fluorescent lamp is by no means the only example of a phosphor glowing in ultraviolet rays.

Imagine a theatre stage with a summer garden, full of flowers and luxurious leafage. Hey presto! and there is a blanket of snow, the trees are bare, and a moon shines high up in the sky.

The secret of the transformation is simple: transparent phosphor paints were used for painting the winter landscape on top of the summer props. When the scenery was illuminated in the usual way, the winter landscape was invisible. But it burst into colour as soon as the mercury lamps were switched on.

Or here is an altogether different field: phosphors help to check the quality of parts at enterprises. If a part is coated with a luminescent compound which is then rubbed off, the phosphor will remain in the crevices, even if ever so tiny, and these can be detected if the part is inspected under ultraviolet rays.

The composition of ores is determined by the radiation of minerals (many of them being natural phosphors). This luminescent analysis as well as luminescent defectoscopy are quite promising as new methods of research.

Luminescence can, however, be excited not only by visible and ultraviolet rays, but by X-rays as well. Thanks to this phenomenon X-rays were discovered late in the last century. In X-ray examination the rays pass through the patient's body and fall on a screen, converting them into light. Naturally, the screen is coated with phosphor.

The TV screen is similar, more or less. It glows due to the impingement of an electron beam from a cathode-ray tube. There is another difference: the luminescent coating of the TV screen consists of instantaneous phosphors, with quickly fading glow, otherwise the change of images would be impossible.

Similar screens were used in the third Soviet artificial Earth satellite for detecting the Sun's particles. These produced flares on the screen which were converted by a photomultiplier into electrical pulses registered by a special device and then transmitted to the Earth by radio.

Radioactive radiation can also provide energy for luminescence. Have you ever thought why the hands of a watch emit light even if it is kept in a pocket for a long time and no "charging" with light is possible? The explanation is that a phosphor of this kind is doped with a radioactive substance, the radiation of which is converted into light.

Finally, luminescence can be caused by thermal or infrared rays, the quanta of which have lower energies than those of visible light. Why? Because these rays merely "release the trigger" cocked either by light or ultraviolet radiation. In this case use is made of phosphors which can store the light they were exposed to for weeks, meanwhile remaining dark. As soon as the infrared quanta hit them, bright flares are produced. In this way Soviet astronomers detected stars the light of which was too weak to be discerned by the eye or even to be photographed.

We could mention many more uses for phosphors. Now they are not only a study of fundamental research, but also an extensive and promising field of semiconductor engineering. But the greatest prospects seem to lie ahead of what is known as electroluminescence which in recent years has branched out into an independent scientific and technical trend.

ANTIPODE OF A SOLAR BATTERY

Coated with zinc sulphide, a lampshade will emit light if a current flows through it. Such sources of light, plates coated with zinc sulphide, already exist and are known as panelescent lamps.

This luminescence, under the action of an electric field, strongly differs from the usual crystalloluminescence. The phenomenon which is new and not yet studied adequately is, according to the current concept, something like a process at work in short-circuited dielectrics.

True, a dielectric is short circuited only in a very strong electric field, while a semiconductor glows in a comparatively weak field. The reason seems to be the concentration of the field around impurities within a phosphor, such as copper sulphide, always to be found in insignificant quantities in sulphurous zinc. This process gives rise to centres of luminescence larger and richer in energy than the centres of crystalloluminescence.

There is yet another difference: in crystalloluminescence a photon is emitted, as we know, only as a result of the encounter of an electron and a positive ion of the activator, while the hole-electron recombination of the semiconductor itself may only release heat. Now, in electroluminescence, the latter recombination is thought to produce light.

The electrophosphor is the antipode of the solar battery. In the latter, light is transformed into electricity. In sulphurous zinc, electric energy is transformed into light. This kind of energy transformation is the most economical of all sources of light, accomplished as it is without either the incandescence of the filament, as in conventional lamps, or the intermediate radiation of mercury vapour, as in fluorescent lamps.

Sulphurous zinc shows luminescence in an alternating current field. Now, carborundum emits light under the action of a direct current and with an efficiency factor close to 100 per cent. In a source like that electrical power is transformed into light practically without loss. Carborundum has another advantage. Sulphurous zinc emits blue or orange rays, not very pleasant to the eye, and so the spectral composition of its radiation has to be improved.

But carborundum needs no improvement in this respect: the light it emits is soft and pleasant.

The only obstacle to manufacturing lamps out of carborundum is its purification. We know what is the cost of the purification of silicon, the melting temperature of which is about 1,400° C. For carborundum it is at least by 400° C higher. Today attempts are made to use rough carborundum crystals for manufacturing sources of light.

It is noteworthy that electroluminescence was discovered more than 30 years ago by the Soviet researcher O. V. Losev who noticed that carborundum detectors were luminescent. First the scientist thought that the cause was the sparkling of a poor contact. His persistent research, however, revealed the true nature of this phenomenon. Losev tackled the problem for the first time in 1923, while the luminescence of sulphurous zinc was discovered by the French scientist Destriau in 1936.

Thus, in this field Losev was far ahead of his time and paved the way for the new trend of illuminating engineering and physics of crystals which only today are making rapid headway.

One of the most amazing inventions in this field is a flat TV screen, proposed by Destriau. The screen is a plate of an electrophosphor of complex composition, with vertical wires on one side and horizontal wires on the other. The wires are connected to an alternating current source; the phosphor emits light at the point where the wires cross and the higher the potential across the wires, the brighter the glow. In the same way each point on the conventional TV screen glows more brightly when a stronger electronic beam hits it.

A flat TV of any size from a cigarette box to a wall is now in the offing.

AN ELECTRIC PRINTER

Several years ago I. I. Zhilevich, a teacher at the Vilnius Pedagogical Institute, decided to simplify and improve book-printing. The conventional process used today takes up too much time and effort. Separate letters are set or lines cast on a very complex machine known as a linotype. Picture blocks are manufactured by a special process. All this is then collected into the form and huge complicated machines press off prints which are then folded and stitched into a book.

By the new process the paper on which the book is to be printed is coated with a thin light-sensitive semiconductor layer. Then the paper is charged electrically by brushing it with a tray of glass with a high tension across it. Finally, a transparent sheet of cellophane with the text is placed on top and the paper is illumined.

Wherever the light falls on the paper, its electric conductivity increases sharply and the charges escape to the areas under the letters of the text. (We are familiar with this process because this is how the charges are redistributed in a semiconductor when heating or illumination is not uniform.)

Now the film with the text is removed and dry paint mixed with metal powder, also electrified in advance, is sprayed over the paper. The text thus "develops", the paint sticking to the charged areas like iron filings to the poles of a magnet. Then the paper is passed under a hot roller, the paint melts, impregnates the paper and sets.

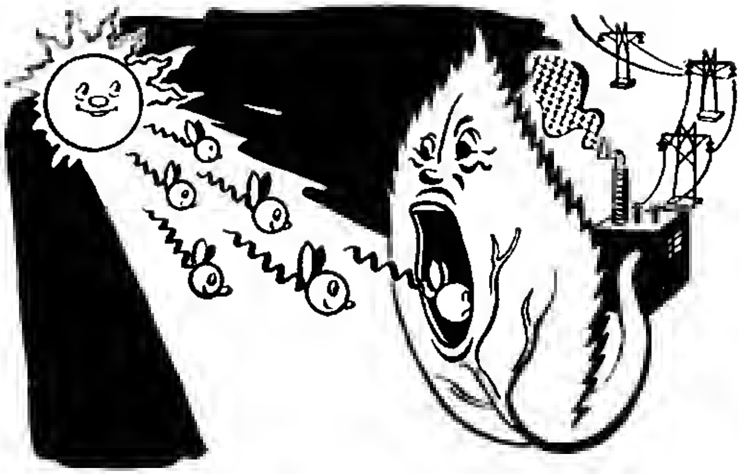
"No sooner said than done," we say. In this particular case, however, the description takes much time while the process itself is instantaneous. The same process can be used for obtaining photographs and drawings, bypassing all photographic stages.

The usual bleached paper possesses a certain electric photosensitivity. But not enough for the printing process.

A new chemical to be deposited on paper has been obtained by Zhilevich and his associates; zinc white is its chief ingredient.

The technique is especially convenient for copying rare books, and copies are much more readable than conventional microfilm.

It is quite possible that before long you will read a book published by a new kind of printer shop, the semiconductor electric printer.



CHLOROPHYLL, ALBUMEN AND THE EYE

GREEN FOCUS OF THE WORLD

The experiment we are going to describe is very simple, so simple indeed that it is difficult to compare it with the process it is intended to simulate. And yet it is precisely this experiment, staged at the Institute of Biochemistry of the U.S.S.R. Academy of Sciences, that furnished the clue to one of the most baffling enigmas of nature.

A glass tube with a green liquid is placed in the sun and the liquid turns red within ten minutes. In the darkness the red changes back into the green.

The tube is a "model" of a leaf and the change of colours reproduces, in a highly simplified manner, a stage of photosynthesis, imperceptible and inseparable in nature from other stages, but the most important of them.

Anyone who happens to pass Nikitskiye Vorota in Moscow sees an austere monument of black stone and a schematic drawing over the inscription "K. A. Timiryazev, Fighter and Thinker" on the pedestal.

The drawing represents the decomposition of carbon dioxide in a leaf under the action of incident solar radiation. This is the epitome of Timiryazev's research, which has immortalised his name.

Our body and our food consist of complicated organic substances. We obtain them from animals and plants. Animals also obtain them ready-made: the carnivora from other animals and the herbivora from plants. Plants are the only "producers" of all things living, all other organisms being merely "consumers". Life, in all the varieties of which we know, owes its existence to the green leaf which alone can make complex organic substances out of simple inorganic materials. It produces carbohydrates, starch and sugar, out of carbon dioxide and water. This process needs light and this is why it is known as photosynthesis. Then more complex substances, albumens and fats, are built out of carbohydrates in the plant.

The leaf absorbs the Sun's energy and conserves it in the compounds it produces. We process these compounds contained in food and thus draw on the energy they contain. Or we burn wood, coal, or oil, using the released heat or light, which is also nothing else but solar energy stored by plants. When dead animals or plants decay, the complex organic molecules which the leaf has built are decomposed and carbon dioxide and water are released. Thus the conversion is continuous in nature.

It has been calculated that almost a thousand million tons of organic compounds oxidise and decompose every day. But fortunately, as many compounds are created in the meantime.

Oxygen is consumed and carbon dioxide is released by breathing, burning or decaying. Plants, on the other hand, consume carbon dioxide and release oxygen, maintaining

thereby a constant composition of the air essential for life. The composition of the air itself is, moreover, attributable to plants. Once there was no oxygen in the atmosphere of the Earth. All oxygen, millions of million of millions of tons of it, has been released by plants. Thus, the plants furnish not only food, but also air for all living things. They have made the Earth what it is.

This is why Timiryazev said that plants perform a cosmic role.

"The green leaf, or rather its microscopic grain of chlorophyll is the focus, the point in the Universe, one end of this point receiving the energy of the Sun and the other giving rise to all creations of life on Earth," he wrote. "The plant is an intermediary between heaven and Earth. It is a true Prometheus who steals fire from heaven. The Sun's ray it has absorbed burns in a sputtering splinter and in a dazzling spark of electricity. The Sun's ray impels the huge flywheel of a giant steam engine, the artist's brush, or the poet's pen."

"I see my blood originating in an ear of grain. . .," said the French scientist Sénebier, one of Timiryazev's predecessors.

How does this Prometheus work?

For a long time it was not even known where from he gets his food. Aristotle believed, for example, that the plant has no stomach and other digestive organs because the soil performs all these duties for it. Organic remains decay in the soil and the plant assimilates them.

Only three hundred years ago this doctrine was put to an experimental test and it was found that the soil lost much less weight than the plant acquired. Then it was decided that it was not the "juices of the Earth", but water that provided the plant with basic food. In another two hundred years it was found that air is the chief source of nutrition for the plant because the air supplies it with carbon.

Thus, more and more became known about the nature of the plant. One of the founders of this science was Timi-

ryazev who made a profound study of the air nutrition of the plant and the laws governing photosynthesis. The research has carried on in many countries and many subtle and sophisticated intricacies in the functioning of the leaf have been revealed.

Still, the chief problem defies solution. How can the leaf or rather its chlorophyll, trap the light pouring on to the Earth and, in Timiryazev's words turn "this most volatile of all forces into an immovable substance"? Photosynthesis is the only process accompanied with, to use a scientific phrase, the increase of the thermodynamic potential (the store of energy), the only process when the energy of the quanta of light absorbed is not wasted, but on the contrary, stored carefully.

Other organisms also synthesise complex substances, of course, and even substances with a large store of energy. Thus, fats are formed of sugars in our body. But this is possible only due to the expenditure of the energy stored by the plant, due to the disintegration of a portion of the same sugars. Only plants produce the initial products, capable as they are of concentrating photon energy.

This is their specific feature, it was said, and there the matter stayed. Now science is about to unravel this enigma, and the new, perhaps decisive step in this direction has been taken by Soviet scientists who staged the experiment we have described.

CHLOROPHYLL AS A SEMICONDUCTOR

The story dates back to research undertaken twenty years ago at the laboratory of Academician A. N. Terenin, of the State Optical Institute in Leningrad. The purpose the researchers had originally set themselves was quite practical: to help industry prevent the fading of pigments.

Substances used for dyeing fabrics absorb light. Photons split the molecules of the pigments which fade as a result. Unlike photosynthesis this is a usual photochemical

reaction when photon energy is not accumulated, but is dissipated.

Objective methods for estimating the photostahility of pigments had to be found. A. T. Vartanyan, a laboratory researcher, decided to determine the electric conductivity of thin hard films of pigment as a function of the absorption of light.

The films proved to be typical semiconductors. The fact was so interesting that a special study was made of their properties. Thus the study of organic semiconductors began.

Then a nonorganic semiconductor was filmed with organic pigment and the film was found to change the light sensitivity of the semiconductor.

We have said that different semiconductors absorb different rays: some infrared rays, others X-rays, still others visible rays. But even in the visible part of the spectrum their sensitivity is not the same. Electrons are released mainly by, say, green rays in some, and by blue rays in others. It is easy to understand why: quanta of different rays have different energies.

It has been found that the nonorganic semiconductor coating of the pigment becomes sensitive to, say, red rays if the pigment ahsorbs red rays. This effect is known as sensibilisation. The discovery made it possible to interpret the familiar facts in new terms, in terms of physics.

Photofilm silver bromide emulsion is known to be sensitive only to violet rays, blue rays, and, much less, to green rays. If a sensitiser is added to the emulsion, it will be sensitive to all visible rays, including yellow and red rays, conveying the relation of colours more faithfully.

Or here is another example. In the preceding chapter we discussed a new method of printing, the dry electrostatic printing technique known as xerography. We mentioned the fact that zinc white (semiconductor zinc oxide being its main component) proved insufficiently sensitive to light and therefore the inventors had to produce a bet-

ter coating for paper. Now you can easily guess that this was achieved by adding a sensitiser to zinc white.

Not every pigment can be a sensitiser. In photography, for example, the search for suitable substances took 30 years. The search was purely empirical until it became obvious that sensibilisation, the transmission of photon energy, is connected with the semiconductor properties of pigments.

Now, chlorophyll is also a pigment. It also has the properties of a semiconductor. True, its electric conductivity is quite insignificant: it is almost an insulator. Its luminescence can be observed, however, in thin films cut off leaves and dried. Illumined and then heated in the darkness, these films will glow. The mechanism is much like that in crystalline semiconductors: an electron disloged by a photon from the atom is trapped in a "pit on the hill", hence it is released due to the thermal agitation, and a new photon results from the recombination.

Of course, dry films are not live leaves, but in the latter chlorophyll also lies in thin layers of minute grains on the albumen "backing".

Finally, it was established beyond doubt that the chlorophyll in the leaf acts as an optical sensitiser: it absorbs nearly all visible rays (mostly red and blue rays) and transmits their energy to the colourless carbon and water which absorb no light at all. Now the vital question—what is the mechanism of this transfer?—could be tackled.

ELECTRON PUMP

The research to answer this question was carried on partly at the same laboratory, but chiefly at the Institute of Biochemistry of the U.S.S.R. Academy of Sciences, also headed by Academician A. N. Terenin. Taking part in the research were A. A Krasnovsky, Dr. Sc. (Biol.), and his colleagues.

They proceeded from the fact that the production of organic substances in the leaf began with the reduction

of carbon dioxide, i.e., its combination with an atom of hydrogen released by a molecule of water. But that takes up four times as much energy as a quantum of a red ray contains and twice as much as does a quantum of a blue ray. What, then, is the actual mechanism of the process? Is the energy of the quanta accumulated by chlorophyll or does the process occur by stages? It was easier to experiment not with the leaf, but with its model.

If a leaf is immersed in alcohol, for example, the chlorophyll readily dissolves and the leaf becomes colourless. Other liquids can be used instead of alcohol. It was one of such solutions of chlorophyll in a tube that served as the model of the leaf.

The water in this model was replaced by ascorbic acid or by other compounds which part with their hydrogen much easier, and carbon dioxide was replaced by substances whose molecules join hydrogen more readily, for example, vitamin B_2 known as riboflavin. The experiments were made in shade and light, at normal and very low temperatures, and each time the spectra of chlorophyll were taken, the electric conductivity of the solution measured, etc.

Chlorophyll furnished information to the explorer's inquisitive mind. The processes at work in the leaf gradually came into view. It appeared that a hydrogen atom was found to be transferred from water to carbon dioxide in stages.

The atom of hydrogen is known to consist of an electron and a proton. Both particles are transferred separately. First of all, the electron is excited in the molecule of chlorophyll when a quantum of light is absorbed: the electron escapes from the conduction band, leaving a hole behind. An electron from the molecule of water fills the hole, while the excited electron of chlorophyll is transferred to the molecule of carbon dioxide.

This is how the electron transfer occurs.

Next follows the proton transfer. This part of the process does not necessarily need light: it takes place in dark-

ness. So the transfer of an electron from water to carbon dioxide starts the process, with the proton transfer following automatically (or aided by ferments).

Each transferred electron brings along a portion of energy which has been spent on its breakaway and shift. All other reactions of photosynthesis, all subsequent complications of its products, are brought about by ferments. But it is chlorophyll that acts as the electron pump.

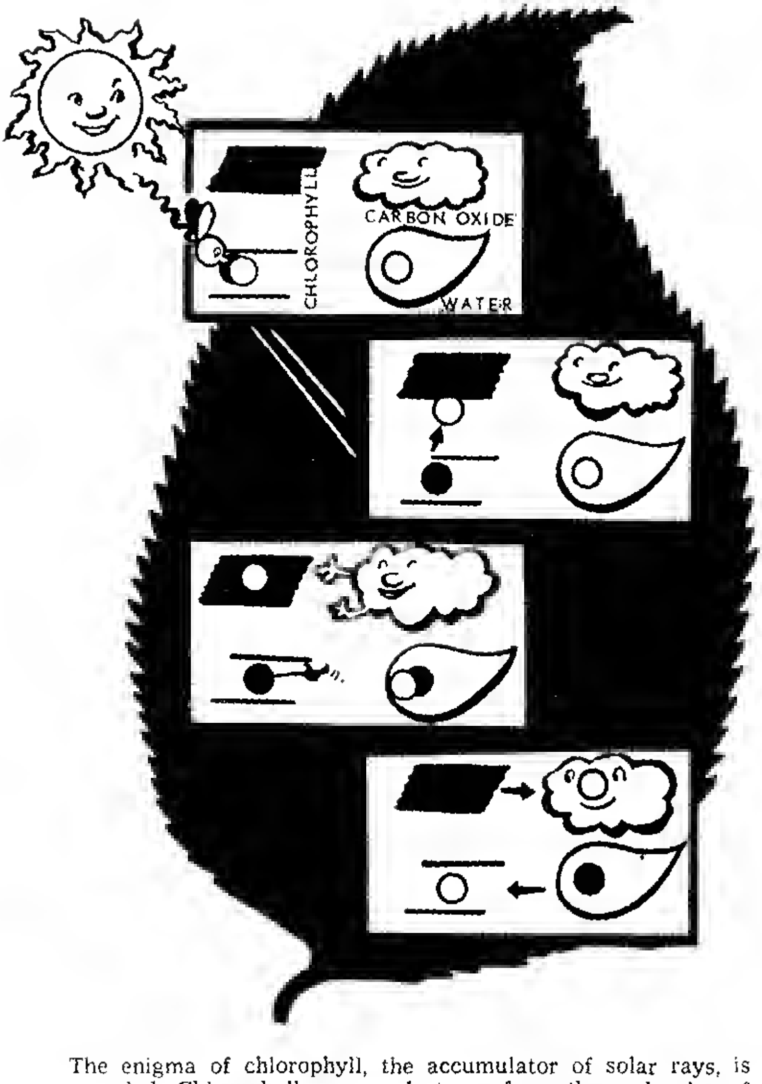
Scientists succeeded in breaking this electron pumping into several stages. If ascorbic acid (hydrogen donor) is added to the solution of chlorophyll, the latter merely takes away electrons from the ascorbic acid. It is precisely in this case that the solution changes its green colour for red after a five- or ten-minute illumination because certain interatomic bindings were violated in the electron-rich molecules of chlorophyll and the substance reacted differently to light. In darkness, however, the colour of the solution is restored, because, failing to obtain more energy, chlorophyll ceases functioning and the electrons return to their original stations.

If riboflavin (hydrogen acceptor) was added to the solution, the process ran through its course and no colour changes of the chlorophyll were perceptible because the chlorophyll was restored too quickly. In this case the process was much like the one which actually takes place in the leaf: first the electron and then the proton were transferred from the donor to the acceptor.

Thus, the first and chief phase of photosynthesis has been reproduced artificially. The significance of this success can hardly be overestimated.

POWER STATIONS OF THE FUTURE

The process observed by the scientists was far more complicated than we have described it. For clarity and simplicity we skipped many details revealed in numerous



The enigma of chlorophyll, the accumulator of solar rays, is revealed. Chlorophyll pumps electrons from the molecules of water to those of carbon dioxide

experiments with chlorophyll as well as other similar substances. Nevertheless, the model of the leaf created as a result of these experiments is still far removed from the original.

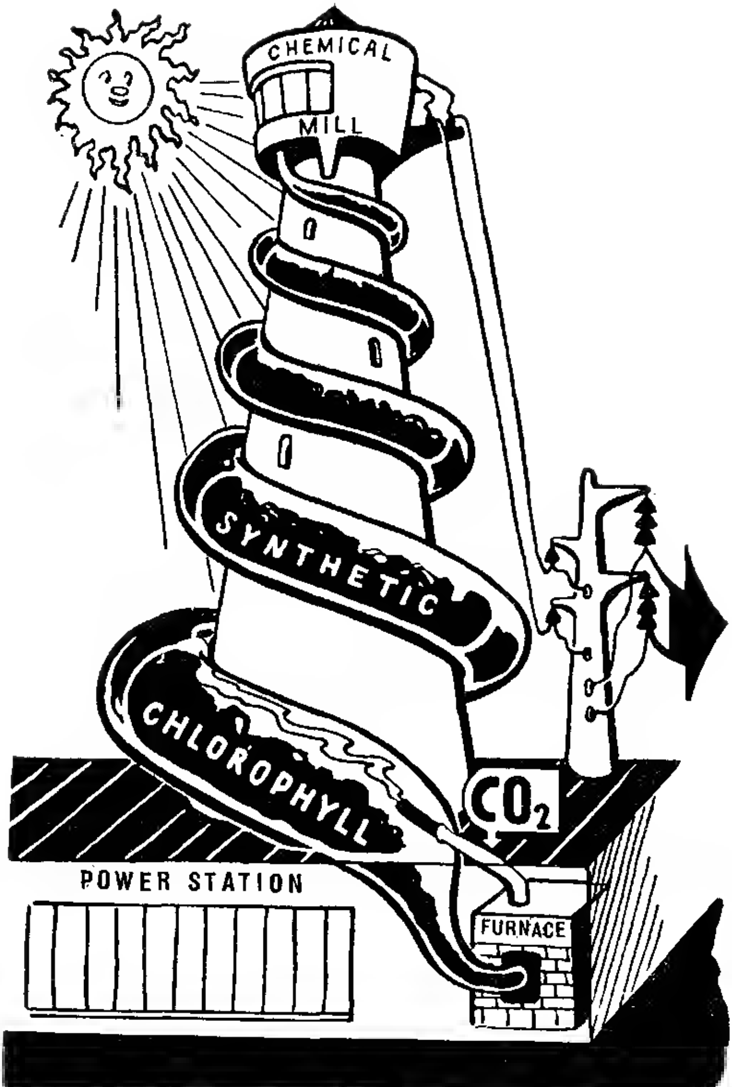
The leaf is an extremely complex living organism. Suffice it to say that photosynthesis ceases once the leaf has been put on a piece of glass and rolled (very gently!) with a glass rolling pin. The leaf which was perfectly normal a minute ago and which had preserved all components and its link with its mother plant has ceased "functioning". Why?

Because photosynthesis is impossible unless a leaf retains its quite definite, highly intricate and subtle structure. This can be disturbed even by the slightest of pressure.

Photosynthesis is akin to catalysis, acceleration of chemical reactions in the presence of certain intermediary substances known as catalysts. This phenomenon is extremely common in nature and engineering. It was a great surprise to learn that nearly all catalysts are semiconductors. Just as in photosynthesis of the leaf, their activity depends on the structure. In general there is evidently much in common between the functioning of chlorophyll and that of a catalyst. It is admitted that the theory of catalysis is far ahead of experiment. Photosynthesis is such a complex study that experimental data in this field are even more scarce.

Opening the All-Union Conference on Photosynthesis in 1946, Academician S. I. Vavilov said that photosynthesis is complex not only because it involves the branches of science already known, but also because it possibly contains new aspects which have eluded observation so far.

Progress has since been made and yet photosynthesis remains a vast, little known field. Besides, the evidence already obtained lends itself to different interpretations. For example, the mechanism of hydrogen transfer which we



A synthetic chlorophyll is another "key to the Sun". Some day chlorophyll will be synthesised and then this is probably what an organic power station will look like

have described above is explained differently by some scientists—not in terms of semiconductor operation, but in conventional chemical terms. In the final analysis, both explanations are only hypotheses helping us to understand an extremely complex process. The new viewpoint, however, receives an ever-stronger following.

In the leaf a whole set of semiconductor mechanisms is probably at work: chlorophyll itself is capable of assuming different states, apart from other pigments present in the leaf. They no doubt co-operate, intensifying by stages the action of each other.

The progress in the study and simulation of photosynthesis suggests that man will eventually learn how to control it. It is a pity that plants do so little for us, though the work they perform is tremendous—they assimilate as much solar energy as could be generated by 200,000 such power stations as the world's most powerful station on the Volga named after the 22nd Congress of the C.P.S.U. We mentioned the fact that plants catch only one per cent of the incident solar energy, while the rest is dissipated back into space. Man must take as much energy from the Sun as he needs. And the truest path towards accomplishing it is perhaps the control of photosynthesis.

"Though I do believe in the future of atomic energy and am convinced of the importance of this invention," said Frédéric Joliot-Curie, "I think that a real revolution in the power industry will come about only when we are able to effect a large-scale synthesis of molecules, similar to chlorophyll, or even on a higher plane."

Let us transfer ourselves to the time when man has accomplished this feat and visualise the photo-organic power station of the remote future.

A chemical plant atop a high tower synthesises chlorophyll, not green, however, but black, to make it a more active absorber of light. A black stream flows down the narrow trough spiralling around the tower. Irradiated by the Sun the stream becomes thicker, like treacle, and ex-

pands. The lower it descends the fuller the trough until the black mass is almost overflowing. Finally, a trough enters the base of the tower, the furnace of the power station, where the organic mass is dried and burned.

Part of electric power is sent upward, to the chemical plant on top of the tower, to maintain the synthesis, while the carbon dioxide leaves the furnace, and goes up under the glass roof of the trough. There is always an excess of carbon dioxide over the black mass and that is why it becomes so treacly.

Thus, the same carbon rotates over and over again, but each time it imbibes a new share of vitalising sunlight.

We have spoken about solar power stations of the near future, photoelectric and thermoelectric stations. Now we may extend the list: photo-organic power stations will be added in time.

Man has dreamed for centuries about trapping the Sun's ray. A vessel with a captured sunray can be found in the legends and fairy-tales of many peoples. Today man is closer to his cherished goal: storing sunshine, synthesising organic substances.

Man will be able to create not only fuel, but any products—quicker and better than the plants do. Man's power will then be unprecedented.

So far experiments on a less ambitious scale are being made. A group of American scientists designed an experimental solar battery out of organic compounds. This little wafer is the size of an aspirin pill, and consists of two layers, as any photocell should. The layers are two different chlorophyll-like substances, both being poor conductors in darkness and good conductors in light. The current that the battery produces is very weak, of course, but anyway the first step in a new and very important direction has been taken.

Nor are the investigators of photosynthesis concerned alone with the transfer of energy in living tissues. In the body of the animal there also occur the break-up of atomic bindings, the regrouping of atoms, the build-up of new compounds and, of course, the transfer of energy—from the decomposed molecule of sugar to the created molecule of fat, for example.

In living tissues energy is transferred practically without loss. The only possible mode of such transfer is via an electric current. Experiments, however, did not support this view.

The principal component of living tissues is albumen. Ferments regulating nearly all reactions in the organism are also albuminous. It was shown experimentally that albumen is an insulator: the conduction band in it is so high above the ground band that at room temperature there is only one free electron in 12 tons of albumen.

The amazingly high efficiency factor of energy transfer in living tissues had remained enigmatic until investigators turned to radiospectroscopy. This extremely subtle and complicated technique showed that in albumen there are free electrons shooting through a molecule at a tremendous speed, thousands of miles per second.

Why couldn't these electrons be detected before? Because they appear for a split second during a biochemical reaction.

This suggested the idea that albumen or ferment is, like chlorophyll, a semiconductor. It shows its semiconductor properties only when it contains impurities, the impurities being precisely those substances which undergo conversion. Some of these, donors, part with electrons, while others, acceptors, absorb them. An electron travels between them in the conduction band along the so-called hydrogen bindings making up a regular network throughout the molecule of albumen. As soon as any of these

bindings are disrupted the electron gets stuck mid-way, just as the leaf loses its ability for photosynthesis when its structure has been tampered with.

The hydrogen binding disruption in albumen is observed during certain mental diseases. A luminescent analysis of the electrical properties of albumen is already used by psychiatrists to check their diagnostic findings.

Studying living tissues radiospectroscopically, the research workers of Laboratory of Anisotropic Structures of the Academy of Sciences of the U.S.S.R. are engaged in the search for synthetics similar to albumen. Probably this will be the way to build up synthetic catalysts.

Whereas the discovery of the semiconductor properties in albumen explained why the transfer of energy in living tissues is so economical, the well-known semiconductor devices, photocells, were instrumental in unravelling another, no less baffling enigma of biology.

To understand how our eye distinguishes colours is the scientist's age-old aspiration. For a long time it was believed, and it is still believed by many, that the retina contains so-called cones of three kinds. These cones were thought to divide the spectrum among themselves, so to speak, waves of different lengths excite different cones, the combination producing the perception of a certain colour.

Soviet investigators have recently discovered, however, that all cones are identical and each of them reacts to all colours, the signals entering the brain via one nervous fibre. These signals consist of separate short pulses of equal strength and duration. It is only the number of pulses, the duration of the whole burst, that differs. This has been proved beyond doubt in experiments with animals. In the frog and the tortoise, for example, a long burst of pulses corresponds to blue and a short burst to red.

It is also important that the cone reacts only to a change of colour, the switching on and off of a lamp. Why do we see it all the time then? Because the eye keeps

shifting from side to side very quickly and spontaneously. The immovable image on the retina vanishes within two or three seconds.

The main thing still remained unclear, however: what happens in the cone when the colour changes—what is the mechanism of colour perception?

M. M. Bongard, a young research worker at the Institute of Biophysics of the Academy of Sciences of the U.S.S.R., built a model of the eye which answers that question. In this model the "cone" is a photoresistive cell and the "brain optic centre" the oscillograph screen with slips of coloured paper pasted on it. If a red lamp is switched on, the red slip on the screen is illuminated in a few seconds. When the red lamp goes out and a blue one flares up, the blue slip is lit up on the screen. The instrument distinguishes colour. How is this achieved?

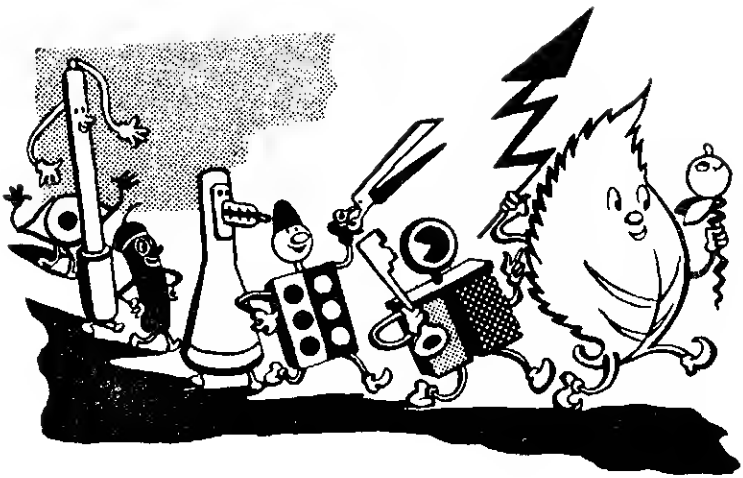
When illuminated or shaded, many semiconductors are known to increase or decrease the current running through them at a different rate, depending on the spectral composition of the light. In selenium, for example, the current increases and decreases more rapidly when the light is blue, than when it is red. The luminosity can be chosen so that the total intensity of the current is equal in both cases. Then the change of the blue light for the red produces a sharp decrease of current; induced by the blue light, the current decreases rapidly and induced by the red light, it increases slowly. The substitution of the blue light instead of the red results in a short-time surge of current. A small computing device between the photoresistive cell and the oscillograph registers the increase or decrease of the current and yields the corresponding signal.

This model conclusively demonstrates that the semiconductor possesses a "colour perception". The cones in our eye are probably semiconductor devices of a kind.

The artificial eye can be tricked rather easily: if the blue lamp is hooded and the hood is then lifted quickly, the

current in the photoresistive cell increases slowly, as it does when the red lamp is on. But the human eye can also be tricked for that matter: if a short red flare is succeeded within 0.04 sec by a similar white flare, one will see only one flare—neither red, nor white, but blue. This is another point of similarity between the eye and the semiconductor.

Thus a new field is developing on the borderland of biology and semiconductor physics. Chlorophyll, albumen and the eye are only the first objects of its study. It is already obvious, however, that semiconductors are of great importance in living nature itself.



NEW AVENUES

Soviet scientists have recently made some discoveries that shed a new light on the nature of semiconductors. Semiconductor properties which crystals alone were thought to possess have now been discovered in amorphous substances, vitreous substances and even some liquids.

Tellurium, for example, remains a semiconductor even in a molten state. Even a very strong heating therefore cannot affect thermoelectric generators: they may melt and harden again as they operate. The temperature range of such generators thus broadens to an unprecedented extent and the efficiency factor rises fabulously.

It is noteworthy that when melting, tellurium hardly changes its density, unlike germanium (as you remember germanium expands as it hardens after the band melting and consequently it contracts as it melts). The electric

conductivity of germanium rises as well: when molten, it becomes a metal conductor. In selenium, on the other hand, both density and conductivity decrease: it becomes much like an insulator in this respect.

All these facts cannot be explained in terms of the "band theory" of semiconductors discussed in the first chapters, since this theory deals only with crystals.

The theory contains other arbitrary simplifications. For example, it likens the electron to the molecule of gas, that is, it assumes that the electron free path (between two collisions) is large, whereas actually it is small for many semiconductors. The band theory does not take into account accurately enough the thermal oscillations of atomic nuclei, crystalline lattice points, assuming that their mean positions or centres of equilibrium are fixed, while actually they shift as temperature changes.

The theory leads to paradoxes sometimes. Thus, all bodies should be phosphors according to the band theory, since they all absorb some quanta of light. The quantum absorbed excites an electron, raising it to a higher energy level. The reverse electron transition is bound to be accompanied by the radiation of light, according to this theory. In reality only substances known as phosphors emit light. In the other substances the transition is radiationless, that is the electron energy is converted into heat. This obvious and well-known fact clashes with the band theory.

Even if we confine ourselves to those materials and processes with which the theory is in good agreement, it cannot yield accurate information as to the choice of a semiconductor and the prediction of its properties.

The band theory played a full part in the development of semiconductor physics. But as time went on, it became clear that the theory had to be improved. Scientists began to work out theories for separate processes to obviate the inconsistencies of the general theory.

Y. I. Frenkel, a well-known Soviet physicist, Corresponding Member of the Academy of Sciences of the U.S.S.R. put forward the exciton theory. The exciton is the excited state of an atom when the electron remains bound with the hole it has left. That accounts for the absorption of quanta of light incapable of releasing electrons.

The exciton may pass from atom to atom. Having obtained a new portion of energy the exciton breaks up, thus releasing the hole and the electron. The reverse may also happen, however: the pair recombines and becomes a bona fide atom. At this either a quantum of light is radiated in the process or the energy is transferred, without radiation, to the crystalline lattice in the form of heat.

E. I. Adirovich, Dr. Sc. (Phys.-Math.), has set forth the radiationless transition theory. The principal difficulty he was confronted with was as follows.

In the light recombination one quantum of light, photon, is produced, while in the thermal recombination the same electron produces several scores, or sometimes even hundreds, of photons, smaller quanta of thermal energy. Yet the atom or crystal lattice point at which the recombination takes place cannot, normally, accept so many photons at a time, nor can the electron part with them one by one. It is this contradiction which led to the conclusion that all bodies ought to be phosphors. Now, where was the way out?

Adirovich established that peculiar conditions arise during the recombination: the centre of equilibrium around which the lattice point oscillates thermally, before recombination, shifts during recombination itself. Imagine a weight balanced on a spring. Hold a strong magnet close to it for a moment. Attracted by the magnet, the weight will get a greater swing. Something like this happens with the crystalline lattice point. Intensified, its oscillations lead to a local overheating, enabling the lattice point to mop up all energy released. As the point settles to equilibrium, it distributes its photons, one by one, among the

neighbouring points. This is what happens when an excited electron returns, radiationless, to its initial level.

Dealing with the electron-free path in a crystal in previous chapters, we concentrated on the effect of the crystalline lattice and its points on the electron. But the electron, in turn, influences the lattice and the lattice may, if the motion is slow enough, react to the appearance of the electron.

The electron, a negatively charged particle as it is, attracts and shifts positively charged ions around it. We know already that the shifts of ions in the crystalline lattice lead to polarisation. The polarised lattice together with the electron responsible for the polarisation is known as a polaron. The polaron travels through the lattice like a wave, without diminishing the mobility of the free electron. It can also be assumed that most of electrons, current carriers, travel in a semiconductor in this way.

Yet even with these amendments the theory does not satisfy researchers today.

Each science may experience such a crisis: accumulation of experimental data reveals the weaknesses of theory. This is what happened with physics at the turn of the century when the famous Michelson experiment showed that contrary to "common sense" no addition of velocities can exceed the velocity of light, 300,000 km per second. When the Einstein theory of relativity came along, the knot was cut, Newtonian mechanics becoming a particular case of the new theory.

Nowadays nuclear physics is also in a state of flux; a stream of new data refashions many concepts. It is quite natural that semiconductor physics is going through a similar stage.

Semiconductors continually reveal new secrets. A thorough study of the properties of individual substances and their chemical structure lead to new theories.

Quite recently semiconductors were stepchildren of science: semiconductor theory was originally moulded

after the pattern of the quantum theory of metals. But a few years later the tables were turned, and in the words of Academician A. F. Yoffe, "semiconductor research became a source of new ideas for the physics of solids". Not merely because metals, like insulators, are, after all, only the extreme cases of semiconductors. The point is that the most complex problem of physics, concerned with the behaviour of the electron in the solid, can be studied best of all in semiconductors. These materials are now the pivot of physics.

While current progress in semiconductor engineering relies on the physical research of the past years, the theory which is now created paves the way for the engineering of the future. And not engineering alone; the alliance of physics and biology opens no less attractive prospects.

As A. F. Yoffe put it: "In modern physics there are two fields from which we expect the greatest changes in the material conditions of life: the atomic nucleus and semiconductors."

Further technological progress depends above all on the advance of the basic fields of physics, and Soviet physicists will concentrate on cosmic rays, nuclear reactions and semiconductors.